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Report 945

METHOD OF PREDICTING COURSE STABILITY AND TURNING QUALITIES OF SHIPS

by
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ABSTRACT

An analytical method combining simplified potential flow theory and low aspect-ratio wing theory with empirical modifications for a real viscous fluid is used to predict the stability derivatives (first order hydrodynamic force and moment derivatives) of a family of hulls in order to estimate the dependence on geometric characteristics of course stability and turning or steering qualities. The hulls are Taylor Standard Series forms with after deadwood removed and have the same length and prismatic coefficient but varying length-draft and beam-draft ratios and skeg area. Comparison between the values calculated by this method and those obtained from experimental measurements shows good agreement. The analytical method can predict the relative effects of the geometrical characteristics. Calculated magnitudes are slightly different from the experimental but are on the conservative side. However, since the hulls tested have the same prismatic, the empirical modification for the rotary moment derivative which is a function of prismatic coefficient has not been fully tested. Necessary refinements of the method must wait on analysis of data on series of forms with different prismatic as well as length-draft and beam-draft ratios.

NOMENCLATURE

A	profile area of wing or hull, ft^2
AR	aspect ratio of wing
B	beam, ft
C_L	dimensionless lift coefficient based on profile area
C_s	two-dimensional lateral added mass coefficient (sectional inertia coefficient)
D	diameter of turning circle, ft
$D_0' = \frac{R_f + R_r}{\frac{\rho}{2}U^2 \ell H}$	total resistance coefficient of the hull
F	force, lb
$F_y' = \frac{F_y}{\frac{\rho}{2}U^2 \ell H}$	measured lateral force coefficient
g	acceleration of gravity
H	maximum draft, ft
h	local draft, ft
h_T	maximum skeg height, ft
I_0	moment of inertia of hull, $lb\text{-}ft\text{-}sec^2$
I_z	added moment of inertia of entrained water (see text), $lb\text{-}ft\text{-}sec^2$
k_1, k_2, k'	Lamb's coefficients of accession to inertia, longitudinal, lateral and rotational
L	lift, lb
$L' = \frac{L}{\frac{\rho}{2}U^2 \ell H}$	dimensionless lift coefficient based on area $\ell \cdot H$
ℓ	length, ft
$m_0 = \frac{\Delta}{g}$	mass of hull, slugs

$m'_0 = \dfrac{m_0}{\frac{\rho}{2}\ell^2 H}$	hull mass coefficient
$m'_1 = k_1 m'_0$	longitudinal added mass coefficient
m'_2	lateral added mass coefficient (see text)
$m'_x = m'_0 + m'_1$	longitudinal virtual mass coefficient
$m'_y = m'_0 + m'_2$	lateral virtual mass coefficient
m'_z	rotational added mass coefficient (see text)
N	yawing moment, lb-ft
$N' = \dfrac{N}{\frac{\rho}{2}U^2\ell^2 H}$	dimensionless yawing moment coefficient
$n'_z = \dfrac{I_0 + I_z}{\frac{\rho}{2}\ell^4 H}$	virtual moment of inertia coefficient
R	radius of turning circle, ft
R_f	frictional resistance, lb
R_r	residual resistance, lb
$r' = \dfrac{\ell}{R}$	dimensionless angular velocity
$s = \dfrac{Ut}{\ell}$	dimensionless distance along the path of the center of gravity of the hull
t	time, seconds
U	velocity of the center of gravity of the hull, ft/sec
$u_x = U \cos \beta$	x-component of U, ft/sec
$u_y = -U \sin \beta$	y-component of U, ft/sec
x, y, z	coordinate axes fixed in the hull with origin at the center of gravity
$\bar{x}$	distance from LCG of center of gravity of lateral added mass, ft
x_p	distance from LCG of center of pressure of lateral force Y, ft
x_T	distance from LCG of center of pressure of tail surface or skeg, ft

x_s, x_b	x-coordinates of stern and bow, respectively
Y	lateral hydrodynamic force, lb
$Y' = \frac{Y}{\frac{\rho}{2}U^2 \ell H}$	lateral hydrodynamic force coefficient
β	yaw angle or drift angle
δ	rudder angle
Δ	displacement of hull, lb
ρ	mass density of the fluid, slugs/ft^3
$\sigma_{1,2}$	stability indices

Subscripts (other than those in above definitions)

H	refers to bare hull
i	refers to ideal fluid
r'	refers to derivative with respect to r'
T	refers to tail surface or skeg
β	refers to derivative with respect to β

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INTRODUCTION

The object of the program whose results are reported here was to develop an analytic method for estimating the course stability and turning or steering qualities of ships. The method, following Martin,[1] was to be based on a combination of simplified flow theory and low aspect-ratio wing theory and was to be assayed by comparison with significant empirical results.

Measurements exist of lateral force and moment, on straight course and in turn (rotating arm tests), on a series of eight models (the "840" Series) having the same parent as the Taylor Standard Series without the deadwood (faired-in skeg) aft (Fig. 1). The models were of the same length and prismatic but with varying beam and/or draft and hence displacement. In addition, there are measurements taken on the models with various flat plate skegs added (Fig. 2), but no other appendages.

Data measured in 1946-47 were reported in refs. 2 and 3 which were concerned primarily with equilibrium turning conditions. Measurements were limited in some cases to a very narrow range of yaw angle around the equilibrium turning angle for a given diameter of turn. For this reason, the data on models with skegs reported in ref. 3 are useless for the purpose of this report. However, unpublished experimental data over a wide range of yaw angle at several turning radii, obtained in 1951 at this laboratory, are available for two of the models with and without a plate skeg extending to the stern. A third hull was tested here in 1959, without skeg and with skegs of various sizes, and an analysis of the data was reported by Tsakonas.[4]

Martin[1] recently reanalyzed the straight course data obtained in 1946-47 on the eight bare hulls along the

lines suggested by Thieme,[5] Inoue[6] and Fedyaevsky and Sobolev.[7] His method of treating the problem of ship motions in the horizontal plane is based on a modified low aspect-ratio wing theory, the Munk ideal moment and cross-flow drag theory. The last was used in estimating the nonlinear force and moment range.

The present work considers only stability derivatives of the first order so that the nonlinear variations, the quadratic and higher terms, may be neglected. Also, since in the linear range the straight-course data are much sparser than the rotating-arm data, it was decided to give more weight to the latter in estimating static stability derivatives. It has been the experience at Davidson Laboratory that entirely reliable static force and moment rates for straight-course motion can be obtained from rotating-arm data at sufficiently large turning radii. This was confirmed in ref. 4 where rotating-arm results were compared with straight-course data measured in Tank No. 3 of Davidson Laboratory using the same towing system and measuring devices as for the rotating-arm experiments in Tank No. 2. In this way, errors attributable to inconsistent mechanisms were avoided. The earlier straight-course data had been measured in Tank No. 1 using different towing and measuring apparatus.

Landweber and Johnson[8] have shown that the simpler methods derived from an alliance of potential flow theory and low aspect-ratio wing theory can estimate the stability derivatives as accurately as sophisticated methods based on more realistic theoretical considerations. The more complex methods employed in ref. 8 require as many simplifying assumptions and empirical correction factors if not of the same kind.

The analytical method adopted here combines the force and moment approximations which were derived for

spheroids from potential flow theory by Lamb[9] and for long slender bodies with tapered or pointed ends by Breslin[10] with Albring's[11] empirical modifications for viscid flow. This approximate method is based on simple concepts, yet correlation can be considered good between calculated and experimentally obtained values. Necessary refinements must wait on the availability of further data on hulls of other prismatic with and without skegs.

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THE ANALYTICAL METHOD

Simplified Flow Theory

In the potential flow theory the hydrodynamic force and moment rate coefficients, or stability derivatives, of an elongated body of revolution without appendages are defined for the linearized region of small angles of attack and large radii of rotation as: on straight course, $r' = \frac{\ell}{R} = 0$

$$\left.\begin{aligned} & L'_{\beta_H} = Y'_{\beta_H} = 0 \\ & \qquad N'_{\beta_H} = m'_2 - m'_1 = N'_{\beta_1} \text{ (Munk ideal moment)} \\ & \text{in turn, around } \beta = 0, \\ & \qquad Y'_{r'_H} = 0 \\ & \qquad N'_{r'_H} = 0 \end{aligned}\right\} \qquad (1)$$

The notation is that of the Society of Naval Architects and Marine Engineers (see Nomenclature and Fig. 3). The measured lateral force coefficient is defined as

$$F'_y = Y' - (m'_o + m'_1)\ r'$$

and its derivative with respect to r' as

$$\frac{\partial F'_y}{\partial r'} = Y'_{r'} - (m'_o + m'_1) \tag{2}$$

where m'_o is the mass coefficient of the hull and m'_1 is the longitudinal added mass coefficient. Lamb,[9] considering the added mass term as a hydrodynamic force, defines $Y'_{r'_H} = - m'_1 = - k_1 m'_o$ where k_1 is the coefficient of longitudinal accession to inertia. Equations 1 are equivalent to those derived by Breslin[10] for a long slender body with tapered or pointed ends from three-dimensional singularity distributions.

The first of eqs. 1 is known to be in serious error in a viscous fluid. To quote Arnstein and Klemperer: "When an airship is propelled at an angle of attack, lift forces are created in a similar manner as by the wing of an airplane. It is true that the airship's shape as a wing is very poor and its aspect ratio extremely small; but the size of the exposed surface is so great that tremendous aerodynamic force components at right angles to the flight path can be evoked."[12]

Fedyaevsky and Sobolev[7] have defined the forces and moments acting on a ship by identifying the body of the ship with a wing. In this analogy the span of the wing is assumed to be double the draft of the ship to take into account the action of the free water surface. Tsakonas[4] shows, by a comparison with the wind-tunnel results of Flax and Lawrence,[13] that this "solid wall" method of accounting for the free surface effect is correct for moderate speeds when the influence of wave making may be neglected.

Albring[11] has derived approximate formulas for the stability derivatives of a body of revolution with and without appendages moving in a viscous and eddying fluid. The lift L on a bare hull is the force developed by the "imagined angle of

of attack at the stern" of a "correspondingly shaped solid without the effect of curvature." It is assumed or taken from experimental measurements. It acts at a distance x_p from the center of gravity and Albring suggests that for most bodies of revolution $x_p = 0$ is a good approximation. For a bare hull his results are given in ref. 11 as:

on straight course, $r' = \frac{\ell}{R} = 0$,

$$\left.\begin{aligned} & L'_{\beta_H} \quad \text{assumed or measured} \\ & Y'_{\beta_H} = L'_{\beta_H} + D'_0 \\ & N'_{\beta_H} = m'_2 - m'_1 + \frac{x_p}{\ell} L'_{\beta_H} \approx m'_2 - m'_1 \approx N'_{\beta_1} \\ & \text{in turn, around } \beta = 0 \\ & Y'_{r'_H} = -\frac{x_p}{\ell} L'_{\beta_H} \approx 0 \end{aligned}\right\} \quad (3)$$

Albring does not give a formula for $N'_{r'_H}$ for the body without appendages. If one assumes that the center of pressure does not shift when going from rectilinear to curvilinear motion, then

$$N'_{r'_H} = -\left(\frac{x_p}{\ell}\right)^2 L'_{\beta_H} \approx 0 \quad (3a)$$

On the other hand, on the basis of Albring's assumption that the center of pressure is unaltered by the addition of fins or skegs, his formula for $N'_{r'}$ for the body with fins should hold for the bare hull:

$$N'_{r'} = -\left(\frac{x_0}{\ell}\right)^2 L'_\beta \quad (3b)$$

where $\frac{x_o}{\ell}$ is implied by Albring to be half the prismatic coefficient of the body. L'_β in this case would be the value for the hull alone, L'_{β_H}, since the effects of the appendages are taken as simply additive.

Equations 3 are derived from simplified flow theory with the necessary condition that in viscid flow the drag is not zero, and so at an angle of attack the lift force is not zero. Under this condition there is an additional moment due to the action of the lift force at a center of pressure displaced from the CG by $x_p \neq 0$. In rotation, the angle of attack at the center of pressure is changed by an amount

$$\tan^{-1}\left(\frac{-x_p r}{U}\right) \approx \frac{-x_p r}{U} \approx -\frac{x_p r'}{\ell}$$

where

r = angular velocity

$r' = \frac{\ell r}{U} = \frac{\ell}{R}$

U = forward velocity

ℓ = length of the hull

R = radius of turn

The additional force coefficient resulting from this change in angle of attack is

$$-L'_\beta \frac{x_p r'}{\ell}$$

and therefore the rotary force derivative of eq. 1 has an additional term

$$\frac{-x_p}{\ell} L'_\beta$$

which is equivalent to the negative of the additional static moment derivative.

In treating the long body equipped with fins, skegs or control surfaces, simplified theory assumes that there is no interference between the body and these surfaces so that their separate effects are additive. Tail-surface (skeg) effects would be derived from the lift on the surface (obtained either by measurements or by assuming the surface to be a wing) by following the reasoning of the previous paragraph. Then

$$
\begin{aligned}
&L'_{\beta_T} \quad \text{assumed or measured} \\
&N'_{\beta_T} = \frac{x_T}{l} L'_{\beta_T} \\
&Y'_{r'_T} = -\frac{x_T}{l} L'_{\beta_T} \\
&N'_{r'_T} = -\left(\frac{x_T}{l}\right)^2 L'_{\beta_T}
\end{aligned}
\tag{4}
$$

where x_T is the algebraic distance between the center of gravity and the center of pressure on the tail (x_T is negative).

Equations 3 and 4 are the basis for the calculation method used in the present report. The assumed lift rates and the other force and moment rates derived from them will be discussed in the following sections.

The Assumed Static Force And Moment Rates For The Bare Hull

The derivative of the lift coefficient with respect to β, L'_{β_H}, is assumed as given by Jones' formula for a low aspect-ratio wing of span equal to twice the ship draft. The dimensionless lift rate per unit wing area

$$\frac{\partial C_L}{\partial \beta} = \frac{\pi}{2}\,AR = \frac{\pi}{2}\left(\frac{2H^2}{A}\right)$$

is derived from the consideration of elliptic load distributions along the chord and the span of a thin foil. Nondimensionalized on the basis of the area H x ℓ, the static rates of eq. 3 become

$$\left.\begin{aligned} L'_{\beta_H} &= \frac{\pi H}{\ell} \\ Y'_{\beta_H} &= \frac{\pi H}{\ell} + D'_0 \\ N'_{\beta_H} &= N'_{\beta_1} + \frac{x_p}{\ell} L'_{\beta_H} = m'_2 - m'_1 + \left(\frac{x_p}{\ell}\right)\frac{\pi H}{\ell} \end{aligned}\right\} \qquad (5)$$

where D'_0 is the drag coefficient obtained from the Taylor Standard Series curves of resistance[14] and x_p is taken as the distance of the center of area of the bare hull profile from the center of gravity.

Tsakonas[4] and Martin[1] found the Jones formula to be a good approximation of the static lift rate of the Standard Series hulls. The fact that the formula does not predict the values obtained from measurements on flat plates of the same profile does not detract from its usefulness for cambered wings. Bisplinghoff proves that an elliptically loaded wing must have an elliptic planform and he points out that it is the so-called flat-plate chordwise distribution which "compares very favorably with the measured chordwise distribution of pressure difference over a slightly inclined, thin, uncambered airfoil developing the same lift. The only significant discrepancies come from within a few per cent chord lengths of the singularity [at the leading edge]."[15] Tsakonas[4] referred to Crabtree's[16] work in substantiation of this statement. Crabtree had found that the pressure distribution over a thin

plate (less than 12% thickness to chord ratio) at various incidences showed a pronounced suction peak near the leading edge with a consequent steep adverse pressure gradient and laminar boundary layer separation. Since the size and form of the separation region or "bubble" has a large effect on the lift, Tsakonas cautioned against use of the experimental measurements on flat plates to predict forces in the case of the ship-wing analogy.

The Assumed Rotary Force And Moment Rates For The Bare Hull

From simplified flow theory the rotary force derivative for a body of revolution without appendages is zero if the body has fore-and-aft symmetry. For a bare ship hull without fore-and-aft symmetry, on the other hand, eq. 3 shows that:

$$Y'_{r'_H} = -\frac{x_p}{\ell} L'_{\beta_H} = N'_{\beta_1} - N'_{\beta_H}$$

and the measured force derivative with respect to r' (eq. 2): (6)

$$\frac{\partial F'_{y_H}}{\partial r'} = -(m'_0 + m'_1) - \frac{x_p}{\ell} L'_{\beta_H}$$

where x_p is different from zero although small.

From eq. 3a:

$$N'_{r'_H} = -\left(\frac{x_p}{\ell}\right)^2 L'_{\beta_H}$$

which is very small. In addition, as shown by Martin,[1] there is a term due to the asymmetry of the rotary added mass of entrained water, m'_z. The moment due to this added mass is $-m'_z r' \bar{x}/\ell$ where $\bar{x}$ is the distance from the center of gravity of the hull to the CG of the lateral added mass.

Then eq. 3a becomes

$$N'_{r'_H} = - m'_z \frac{\overline{x}}{\ell} - \left(\frac{x_p}{\ell}\right)^2 L'_{\beta_H} \tag{6a}$$

If eq. 3b is used

$$N'_{r'_H} = - m'_z \frac{\overline{x}}{\ell} - \left(\frac{x_0}{\ell}\right)^2 L'_{\beta_H} \tag{6b}$$

where x_0/ℓ is half the prismatic coefficient. The values obtained from eq. 6b have been found to be much closer to experimental results than those calculated by eq. 6a. The second term of eq. 6b is approximately 1-1/2 times the first. For this reason, eq. 6b has been taken as the assumed rotary moment rate. As in ref. 1, m'_z and $\overline{x}$ have been estimated in the following way:

$$m'_z = \frac{k'}{k_2} m'_2 = \frac{k'}{k_2} \frac{m_2}{\frac{\rho \ell^2 H}{2}}$$

$$m_2 = k_2 \frac{\rho \pi}{2} \int_{x_s}^{x_b} C_s h^2 \, dx$$

k_2, k' are Lamb's coefficients of accession to inertia, lateral and rotational.

x_s, x_b are the x coordinates of the stern, bow.

h = local draft

C_s = two-dimensional lateral added mass coefficient. It is determined at each section from the curves on two-dimensional forms of Lewis' sections by Prohaska.[17]

$$\bar{x} = LCG - \frac{\int_{x_s}^{x_b} C_s h^2 x\,dx}{\int_{x_s}^{x_b} C_s h^2\,dx}$$

The Stability Derivatives
For Hulls With Skegs

The force and moment derivatives for the hulls with skegs are taken as a simple addition of the corresponding forms of eqs. 6 and 4:

$$\left.\begin{aligned}
L'_{\beta} &= L'_{\beta_H} + L'_{\beta_T} \\
Y'_{\beta} &= Y'_{\beta_H} + L'_{\beta_T} \\
N'_{\beta} &= N'_{\beta_H} + \frac{x_T}{\ell} L'_{\beta_T} \\
Y'_{r'} &= Y'_{r'_H} - \frac{x_T}{\ell} L'_{\beta_T} \\
N'_{r'} &= N'_{r'_H} - \left(\frac{x_T}{\ell}\right)^2 L'_{\beta_T}
\end{aligned}\right\} \tag{7}$$

In the present nondimensionalized form of Jones' formula

$$L'_{\beta_T} = \frac{\pi h_T}{\ell} \tag{8}$$

h_T = maximum skeg height

The center of pressure of the skeg will be assumed at the after end of the skeg. Since the length of the skeg is small in comparison with the length of the hull, any error involved in this assumption will be small.

For the case of models with skegs extending to the stern (Fig. 2), these formulas give essentially the same results as those obtained by the method suggested by Martin.[1] He included the following terms in his force and moment equations, respectively, to account for the skeg effect:

$$- m(x_s)u_x\ (k_2 u_y + k'r\ x_s) \quad \text{(from eq. 2 of ref. 1 for } F_y) \tag{9a}$$

and

$$- x_s\ m(x_s)u_x\ (k\ u_y + k'r\ x_s)\ \text{(from eq. 3 of ref. 1 for N)} \tag{9b}$$

where

$m(x_s)$ = two-dimensional lateral added mass at the stern per ft

u_x = $U \cos \beta \approx U$

u_y = $-U \sin \beta \approx -U\beta$

r = angular velocity of the ship.

When the section at the stern is that of a flat plate,

$$m(x_s) = \frac{\rho \pi H^2}{2}$$

(see Kuerti, McFadden and Shanks[18])

and this term is numerically the same as that given by the Jones formula for a low aspect-ratio wing of span equal to twice the ship draft. After nondimensionalizing, since $k_2 \approx k' \approx 1$, eq. 9a for the added force is approximately

$$L'_{\beta_T} (\beta - r' \frac{x_T}{\ell})$$

and eq. 9b for the added moment is

$$L'_{\beta_T} \frac{x_T}{\ell} (\beta - r' \frac{x_T}{\ell})$$

where L'_{β_T} is given by eq. 8. Then the force and moment rates are those given in eq. 4.

The Stability Indices

The criteria for inherent dynamic stability of a free body moving on straight course in the horizontal plane are the damping exponents σ_1 and σ_2 in the solution

$$\beta = \beta_1 e^{\sigma_1 s} + \beta_2 e^{\sigma_2 s}, \quad r' = r'_1 e^{\sigma_1 s} + r'_2 e^{\sigma_2 s}$$

of the homogeneous linearized equations of motion[18]

$$\left.\begin{aligned} (m'_x - Y'_{r'}) r' - m'_y \beta_s - Y'_\beta \beta = 0 \\ n'_z r'_s - N'_{r'} r' - N'_\beta \beta = 0 \end{aligned}\right\} \qquad (10)$$

where Y'_β, N'_β, $Y'_{r'}$ and $N'_{r'}$ are defined in eqs. 6 and 6b for the bare hull and in eq. 7 for the hull with skegs.

$$m'_x = m'_0 + m'_1$$

$$m'_y = m'_0 + m'_2$$

$$n'_z = \frac{I_0 + I_z}{\frac{\rho}{2}\ell^4 H}$$

$$\frac{I_0}{\frac{\rho}{2}\ell^4 H} = \frac{m'_0}{16} \text{ (assuming the radius of gyration is equal to } \tfrac{\ell}{4}\text{)}$$

$$I_z = k' \frac{\pi\rho}{2} \int_{x_s}^{x_b} C_s \, h^2 x^2 dx \qquad \text{(ref. 1)}$$

and

$$\beta_s = \frac{\partial\beta}{\partial s}, \quad r'_s = \frac{\partial r'}{\partial s}, \quad s = \frac{Ut}{\ell}$$

Solution of the characteristic equation of eq. 10 gives the roots

$$\sigma_{1,2} = \frac{-(n_z' Y_\beta' - m_y' N_{r'}') \pm \sqrt{(n_z' Y_\beta' - m_y' N_{r'}')^2 + 4 n_z' m_y' \left[N_{r'}' Y_\beta' + (m_x' - Y_{r'}') N_\beta'\right]}}{2 n_z' \, m_y'} \tag{11}$$

If σ_1 and σ_2 (or their real parts) are both negative, the motion is inherently stable in that an initial disturbance damps out exponentially; the more negative the exponents, the sooner it damps out and hence the greater the stability. If σ_1 is positive, the motion is unstable and the hull cannot keep to a straight course without application of a corrective rudder.

The turning characteristics of a hull in turns that are not too tight (when nonlinearities can be neglected) can be predicted qualitatively from the σ_1 index. A more dynamically stable hull will turn in a larger radius under a given applied rudder force than will a less stable hull. Conversely, the more stable hull will require greater rudder force than the less stable hull to turn in a given radius. On the other hand, an unstable body may turn in the opposite direction to that indicated by the applied rudder and will need a comparatively large force to bring it around (until it becomes stable in the turn, but stability in turn is outside the scope of this report).

PRESENTATION AND DISCUSSION OF RESULTS

The experimental data measured in 1946-47,[2,3] 1951 (unpublished), and 1959,[4] are shown in Figs. A-1 to A-48 in the Appendix, plotted in dimensionless form versus dimensionless angular velocity $r' = \ell/R$ and yaw angle β. Figures A-1 to A-19 present the measured lateral force coefficients $F'_y = -(m'_o + m'_1)\ r' + Y'$ and Figs. A-20 to A-38 the measured yawing moment coefficients N' for the bare hulls. Figs. A-39 to A-48 show these quantities for three of the hulls equipped with skegs but no other appendages. Skeg 20 or A is the full skeg extending to the after perpendicular (Sta. 20), skeg 18 or B extends to Sta. 18, 0.1 length from the after perpendicular, and skeg 17 or C to Sta. 17, 0.15 length from the after perpendicular.

The experiments had been conducted at speeds ranging from length-Froude numbers of 0.16 to 0.23, for which range the implication of the analytical method that wave making may be neglected is valid. In that speed range the ratio of force or moment to the square of speed changes only slightly so that data measured at different speeds within the range can be compared legitimately.

Table I gives the pertinent characteristics of the eight hulls and the necessary information for the calculations. The resistance coefficients $D'_o = 2\ (R_f + R_r)/\rho U^2 \ell H$ were taken from the Taylor Standard Series curves[14] as the average of the slightly different values for Froude numbers 0.16 and 0.23.

The calculated $Y'_\beta \beta$ and $N'_\beta \beta$, force and moment coefficients respectively at $r' = 0$, are also shown on the data charts in the Appendix. The data plotted at various β versus r' are faired to the calculated values at $r' = 0$ with no stretch of the imagination. The static force and moment rate coefficients are the same whether predicted by the analytical method or by rotating-arm data.

Figures 4 through 9 in the text are summary charts comparing experimentally obtained values for the rotary as well as static derivatives with those calculated by the analytical method. These values are shown for varying length-draft ℓ/H and beam-draft B/H ratios.

The calculated $\partial F_y'/\partial r'$, N_r', and stability indices $\sigma_{1,2}$ predict the variations with ℓ/H and B/H correctly but underestimate the actual magnitudes slightly in the bare-hull cases, more in the cases of hulls with skegs. The quantitative predictions, however, are on the conservative side. These comparisons suggest that the simple method adopted here can be useful for estimating the stability of a given vessel. The good results justify use of the ship-wing analogy and the Jones formula for the lift on the ship as a low aspect-ratio wing.

The following are specific deductions from the charts:

1. The static force derivative Y_β' varies inversely with ℓ/H (or directly with aspect ratio) and directly with B/H although B/H has very slight effect. Y_β' is increased by adding skeg area. An increase in Y_β' is in the direction of greater stability.

2. The static moment derivative N_β' also varies inversely with ℓ/H and directly with B/H. This destablizing moment rate is reduced mainly by increasing ℓ/H and by adding skeg area at the stern.

3. The rotary force derivative $\partial F_y'/\partial r'$ becomes less negative or more positive by increasing ℓ/H, by decreasing B/H and by increasing skeg area at the stern. As in the case of N_β', increasing ℓ/H or decreasing B/H is in the direction of greater stability. The variation with B/H arises from the variation in the longitudinal virtual mass coeffi-

cient. This is the most important effect for the bare hulls, and is as important as the skeg effect in the case of hull with full skeg.

4. The rotary moment derivative $N'_{r'}$ is independent of B/H. It becomes less negative with increasing ℓ/H and more negative (towards greater stability) when skeg area is added at the stern. The variation with ℓ/H is slight in the case of the bare hulls, more pronounced for the hulls with skegs.

5. The stability indices $\sigma_{1,2}$, which combine the effects of static and rotary force and moment rates, show that stability depends almost entirely on B/H and very little on ℓ/H in the range tested. Stability increases as B/H decreases. On the other hand, an increase in B/H would result in greater turning ability.

Figure 10 is a summary chart comparing the calculated Y'_β, N'_β, $Y'_{r'}$, $N'_{r'}$ and σ_1 with the values from measurements obtained by Tsakonas[4] in 1959 on the 842 hull, without skeg and with three skegs of different sizes. The calculated static derivatives Y'_β and N'_β are identical with those obtained from experimental results. This is also shown in Figs. 4 and 7. Figure 10 shows that while the calculated and experimental magnitudes of the rotary derivatives and stability index differ slightly, the stability predictions are conservative estimates. It is also seen that the analytical method can predict the trend in stability with increase in skeg area. Figures 11 and 12 for the hitherto unpublished 1951 data confirm these conclusions.

CONCLUSIONS AND RECOMMENDATIONS

An analytical method for estimating course stability and turning qualities of ships has been developed and compared with available experimental data on a series of eight hulls, the 840 Series, of the same length and prismatic but varying in draft and/or beam and displacement. The analytical method combines simplified flow theory with low aspect-ratio wing theory and makes use of Albring's empirical modification for the rotary moment derivative.

Encouragingly good correlation is shown between the calculations by this method and the results based on the experimental data. However, since the 840 Series is a family of hulls of the same prismatic, Albring's modification for the rotary moment rate which is a function of prismatic coefficient has not been fully tested. Necessary refinements of the method must wait on analysis of data on hulls of other prismatic, with and without skegs or deadwood aft.

It is recommended therefore that all available data on hydrodynamic forces and moments, in turn, for other hull forms with different prismatic as well as length-draft and beam-draft ratios be assembled and analyzed with a view to checking and refining the method. It would also be advisable to do further experimentation in still water on families of hulls such as the Series 60. The latter series has been the subject of extensive tests to determine resistance, bending moments and sea-keeping qualities in waves but the stability on straight course and behavior in turn have so far been investigated for only one of the series.[20]

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TABLE I

PERTINENT CHARACTERISTICS OF THE 840 SERIES HULLS (Taylor Standard Series)

Model No.	841	842	843	844	845	846	847	848
Length ℓ, ft	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Beam B, ft	0.551	0.870	1.375	0.551	1.375	0.870	0.870	0.691
Draft H, ft	0.188	0.298	0.471	0.298	0.298	0.188	0.471	0.236
Displacement Δ, lb	19.40	48.40	121.00	30.50	76.50	30.50	76.50	30.50
Prismatic Coefficient C_p (= $^{2x}0/\ell$)	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
LCG/ℓ, from bow	0.481	0.481	0.481	0.481	0.481	0.481	0.481	0.481
(R-740, 1959)		0.520						
B/H	2.92	2.92	2.92	1.85	4.62	4.62	1.85	2.92
ℓ/B	10.89	6.90	4.36	10.89	4.36	6.90	6.90	8.68
ℓ/H	31.90	20.13	12.74	20.13	20.13	31.90	12.74	25.42
Lamb's Coefficients of Accession to Inertia for Equivalent Ellipsoids								
Major axis/minor axis, ℓ/2H	15.95	10.06	6.37	10.06	10.06	15.95	6.37	12.71
k_1 (longitudinal)	.012	.020	0.40	.020	.020	.012	.040	.017
k_2 (lateral)	.978	.960	.920	.960	.960	.978	.920	.967
k' (rotational)	.935	.885	.772	.885	.885	.935	.772	.902
Other Physical Characteristics								
m'_o, mass coefficient	.092	.145	.229	.092	.229	.145	.145	.115
m'_1, longitudinal added mass coefficient	.001	.003	.009	.003	.003	.002	.009	.002
m'_2, lateral added mass coefficient	.083	.129	.194	.128	.130	.084	.192	.103
m'_z, rotational added mass coefficient	.079	.119	.163	.118	.120	.080	.161	.096
n'_z virtual moment of inertia coefficient	.0107	.0165	.0245	.0131	.0218	.0141	.0191	.0132
$\overline{x}/\ell$, CG of lateral added mass from LCG	.070	.070	.070	.070	.070	.070	.070	.070
(R-740, 1959)		.110						
x_p/ℓ, center of area of profile from LCG	.052	.052	.052	.052	.052	.052	.052	.052
(R-740, 1959)		.091						
D'_o	.014	.014	.015	.011	.020	.018	.011	.014

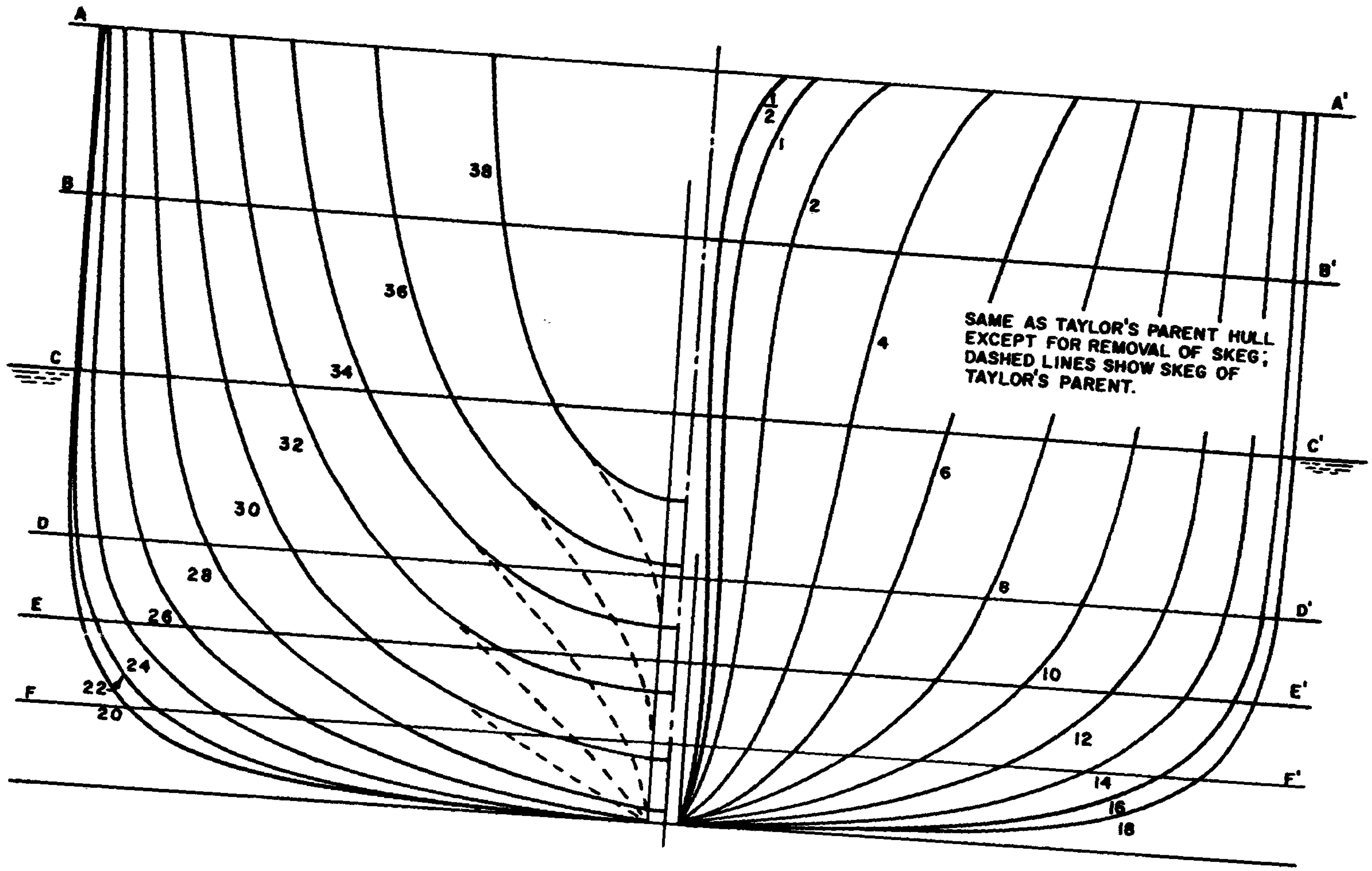


FIGURE 1. BODY PLAN OF MODEL PARENT

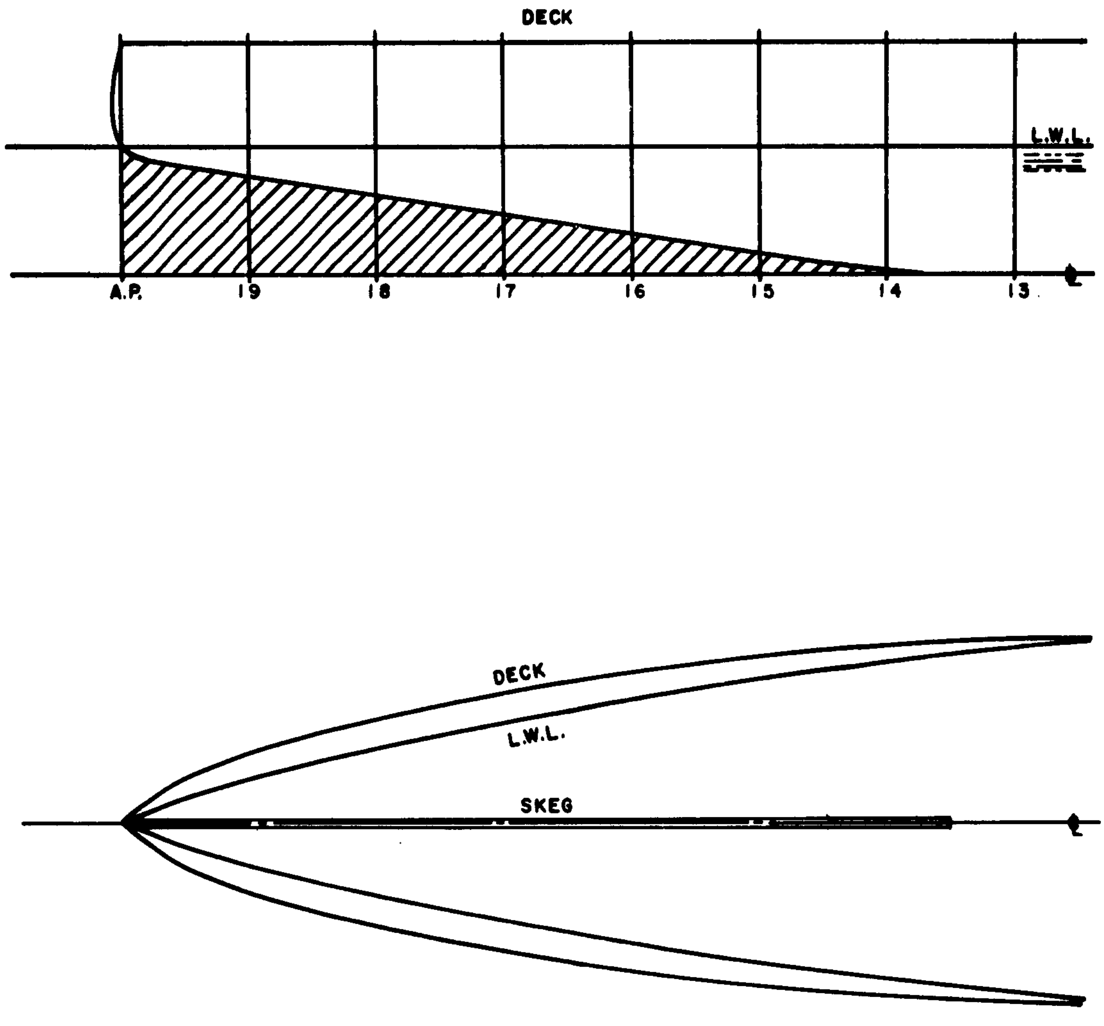


FIGURE 2. SKEG 20 INSTALLED ON MODEL

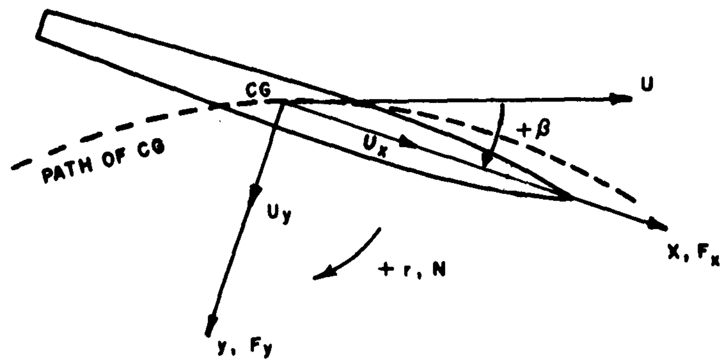


FIGURE 3. MODEL ORIENTATION IN X-Y PLANE

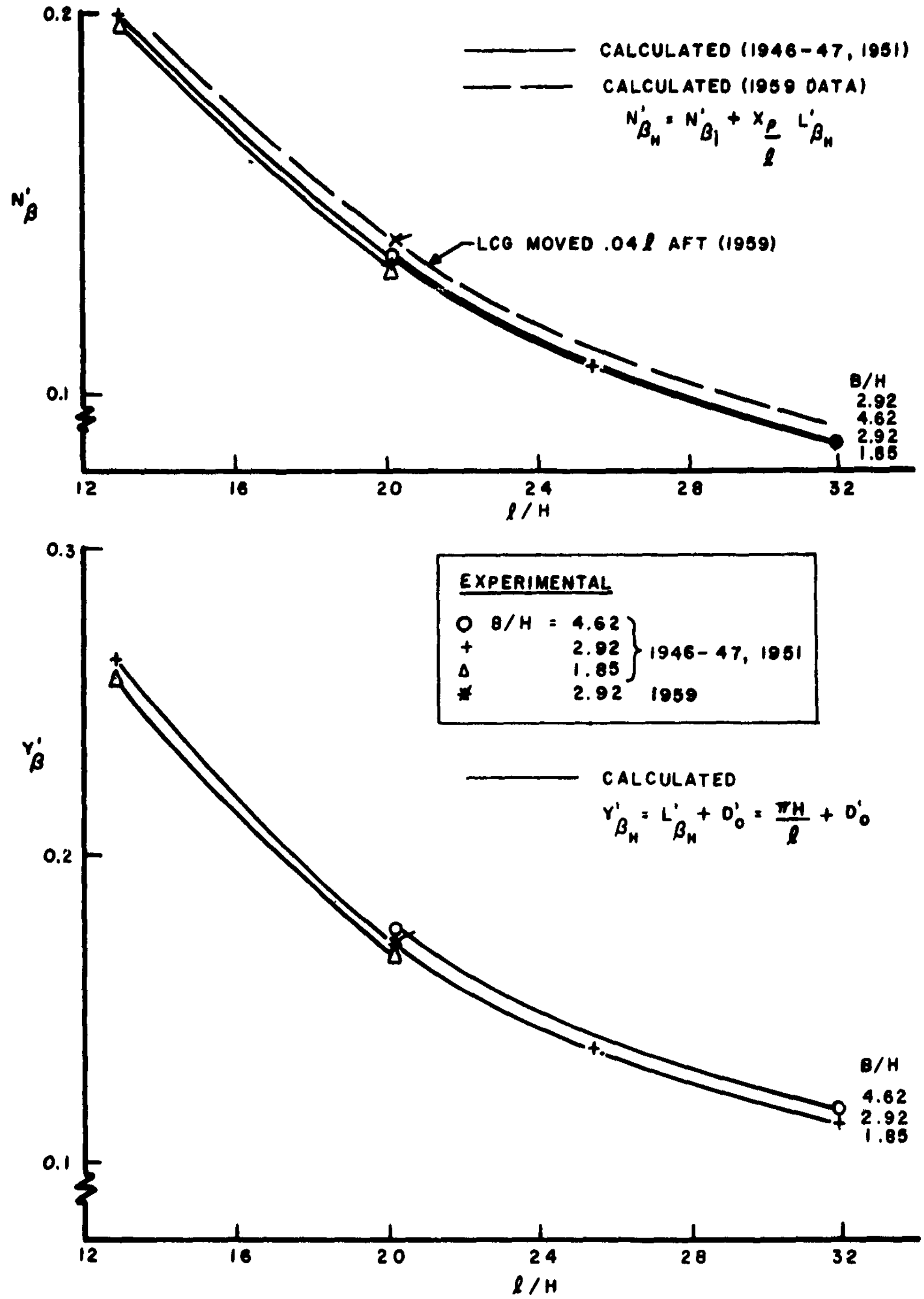


FIGURE 4. 840 SERIES BARE HULLS DERIVED FROM TAYLOR'S STANDARD SERIES WITHOUT DEADWOOD AFT PRISMATIC COEFFICIENT C_p = 0.54

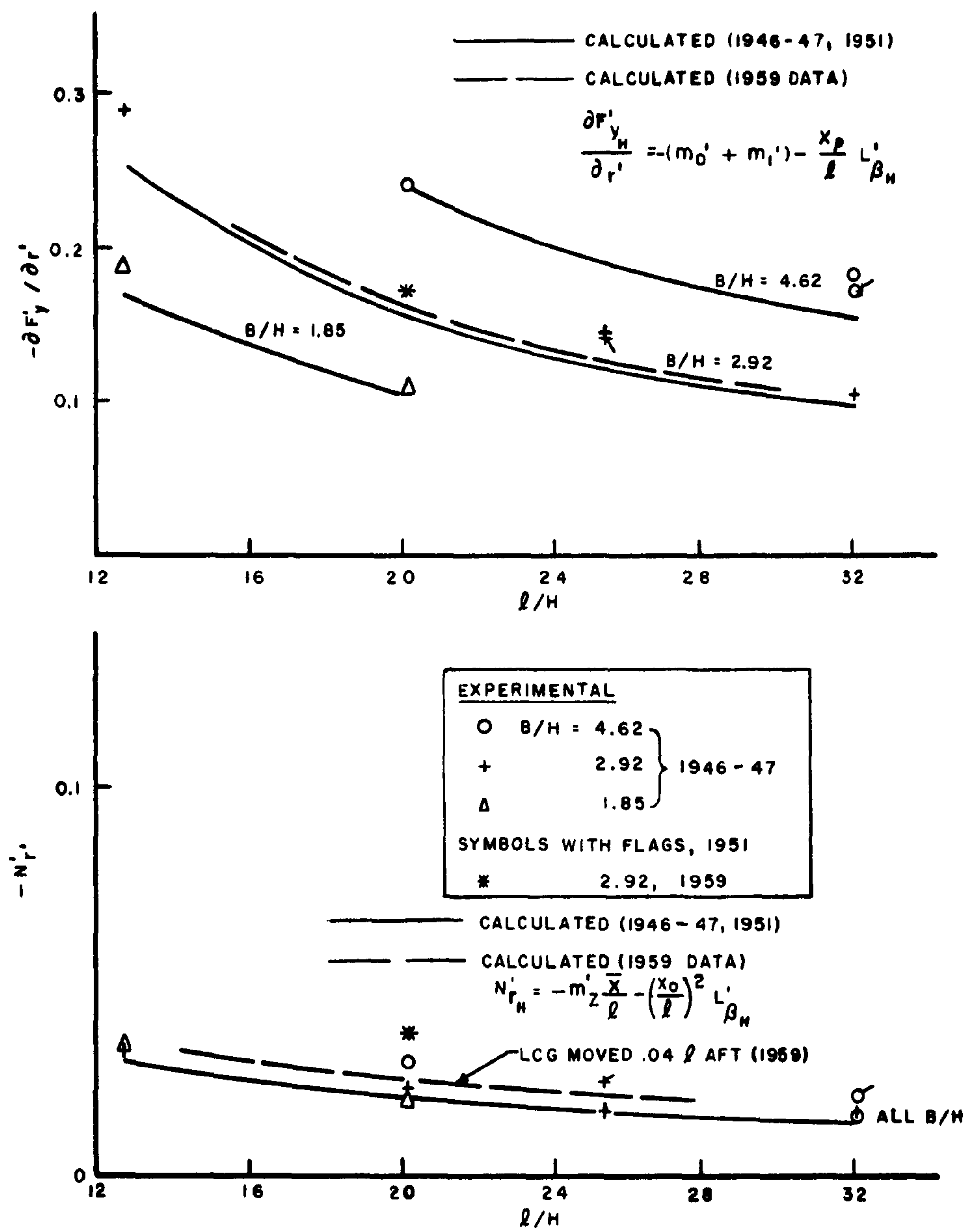


FIGURE 5. 840 SERIES BARE HULLS

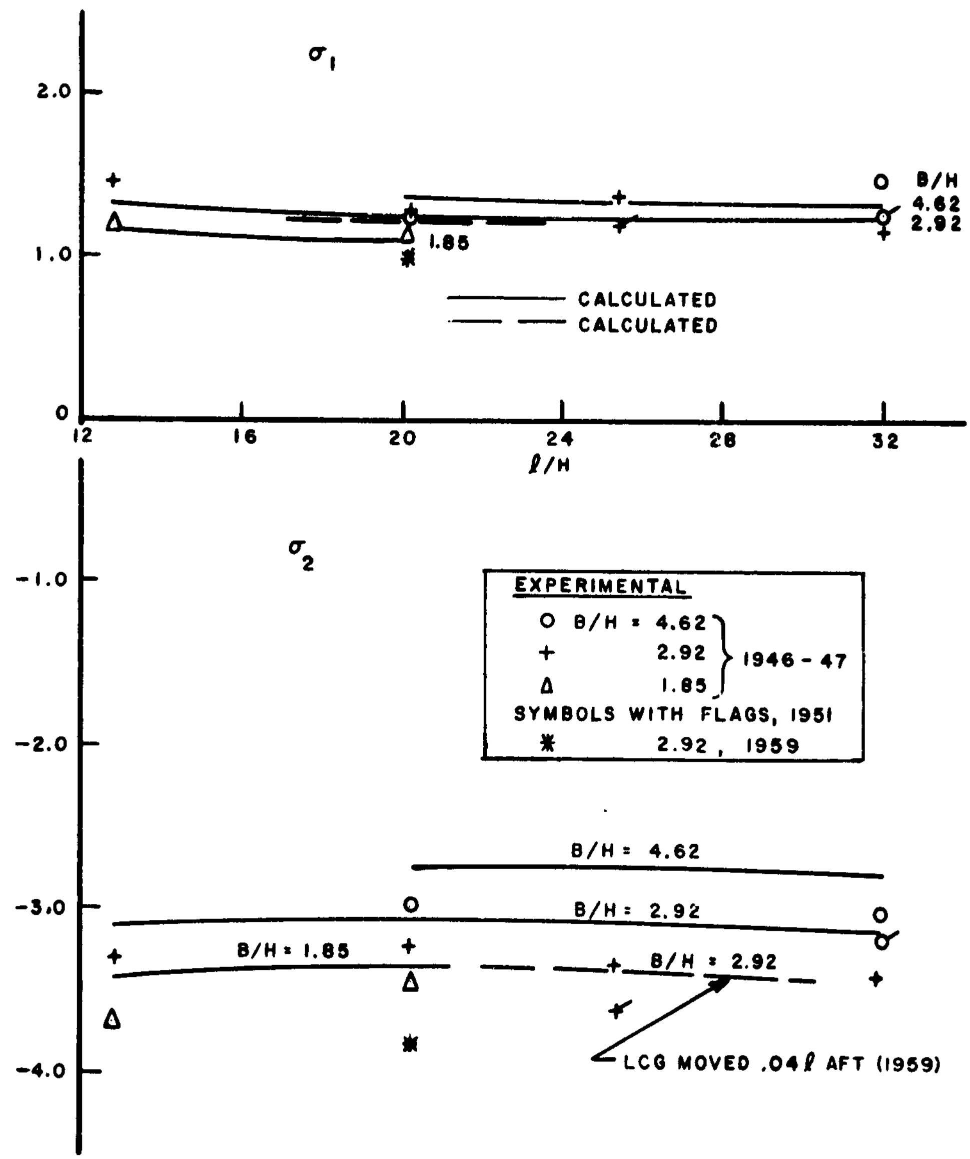


FIGURE 6. 840 SERIES BARE HULLS, STABILITY INDICES

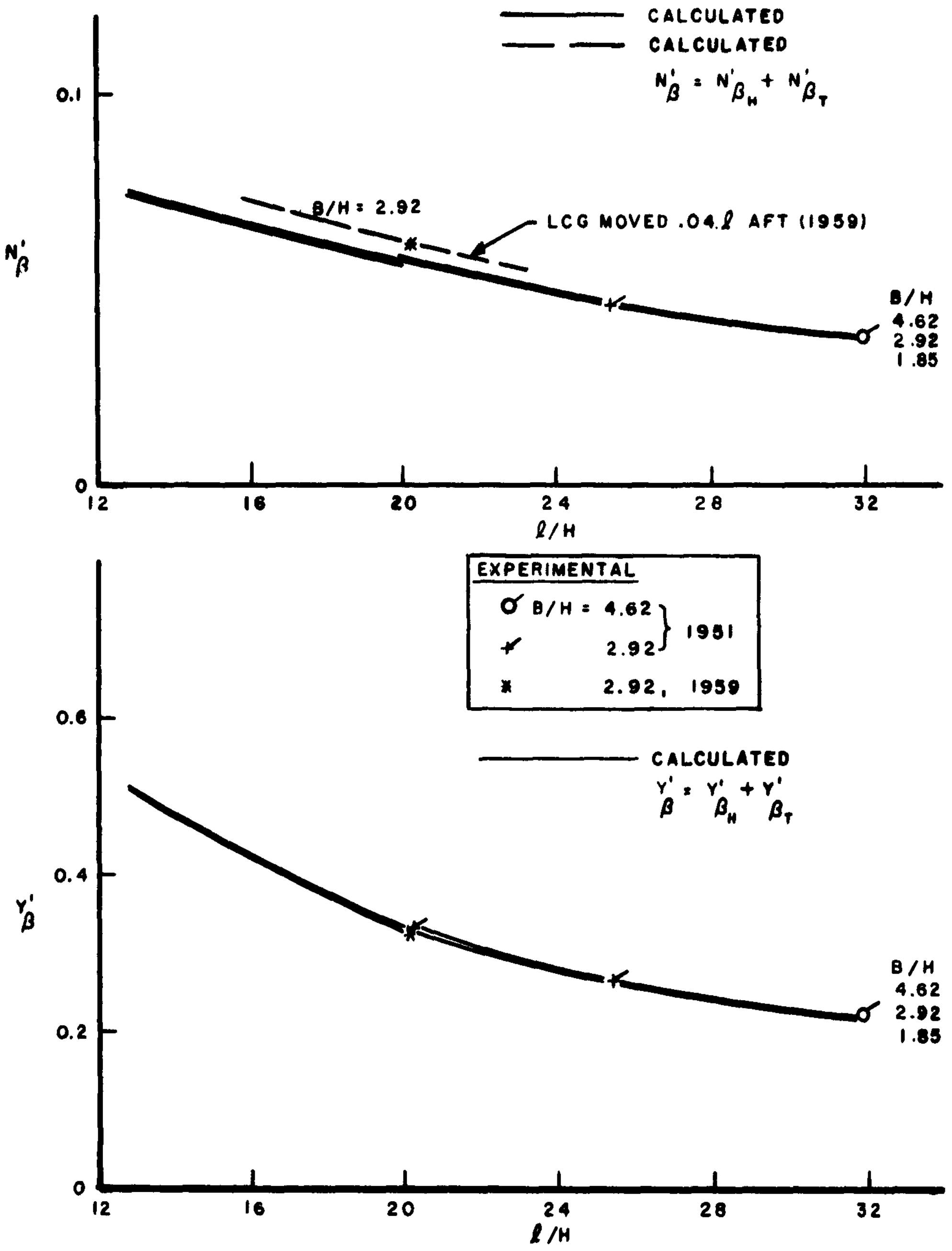


FIGURE 7. 840 SERIES HULLS WITH FULL SKEG (20)

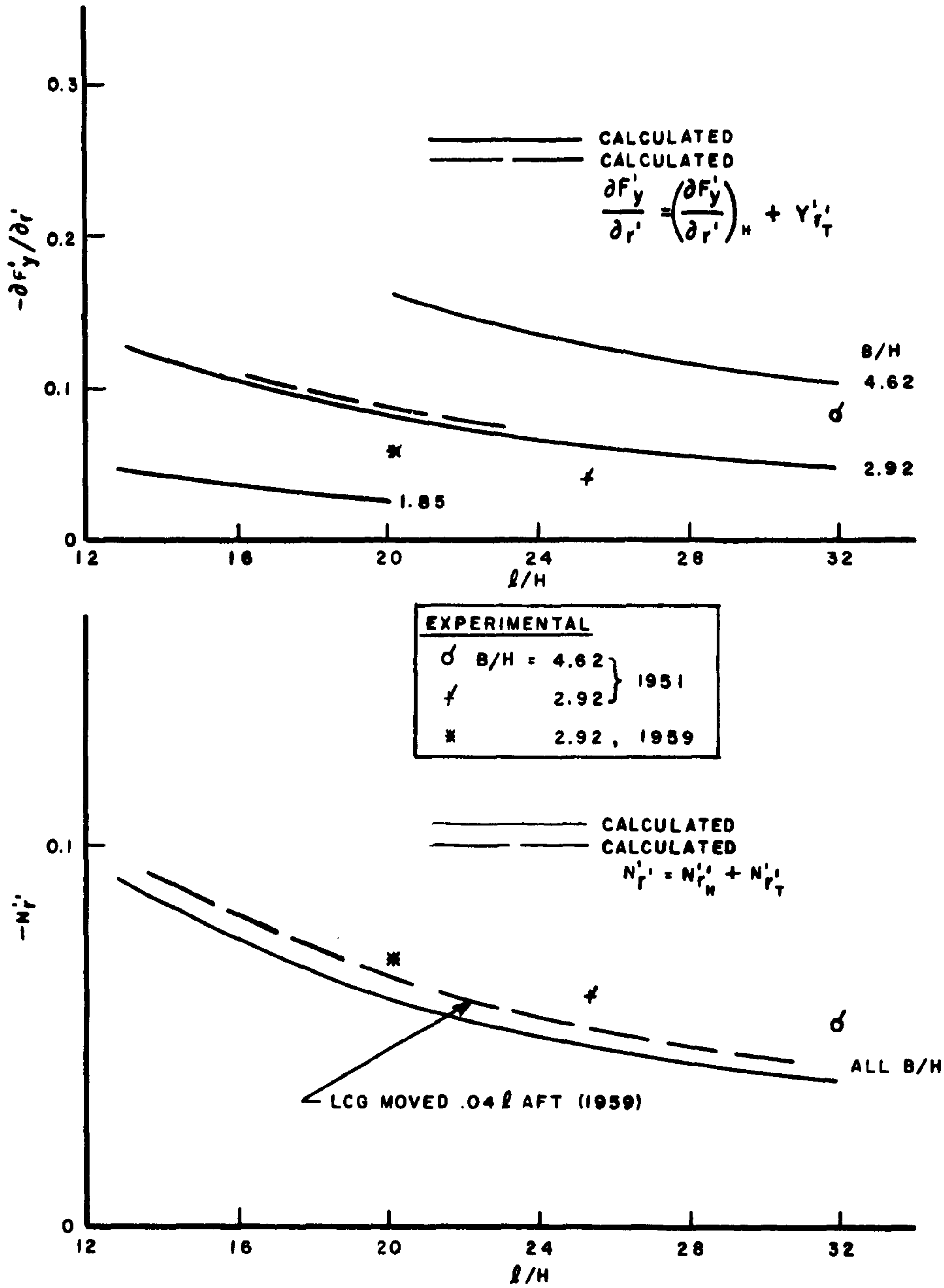


FIGURE 8. 840 SERIES HULLS WITH FULL SKEG (20)

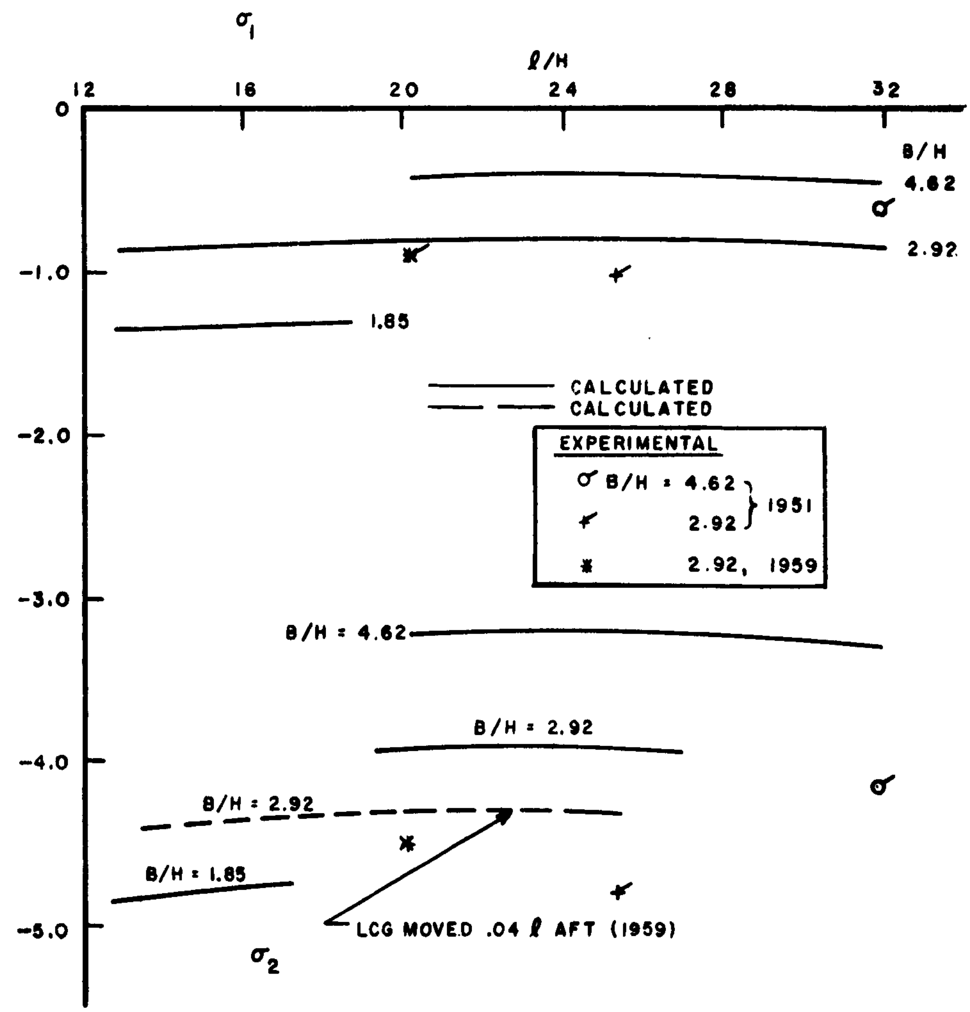


FIGURE 9. 840 SERIES HULLS WITH FULL SKEG (20) STABILITY INDICES

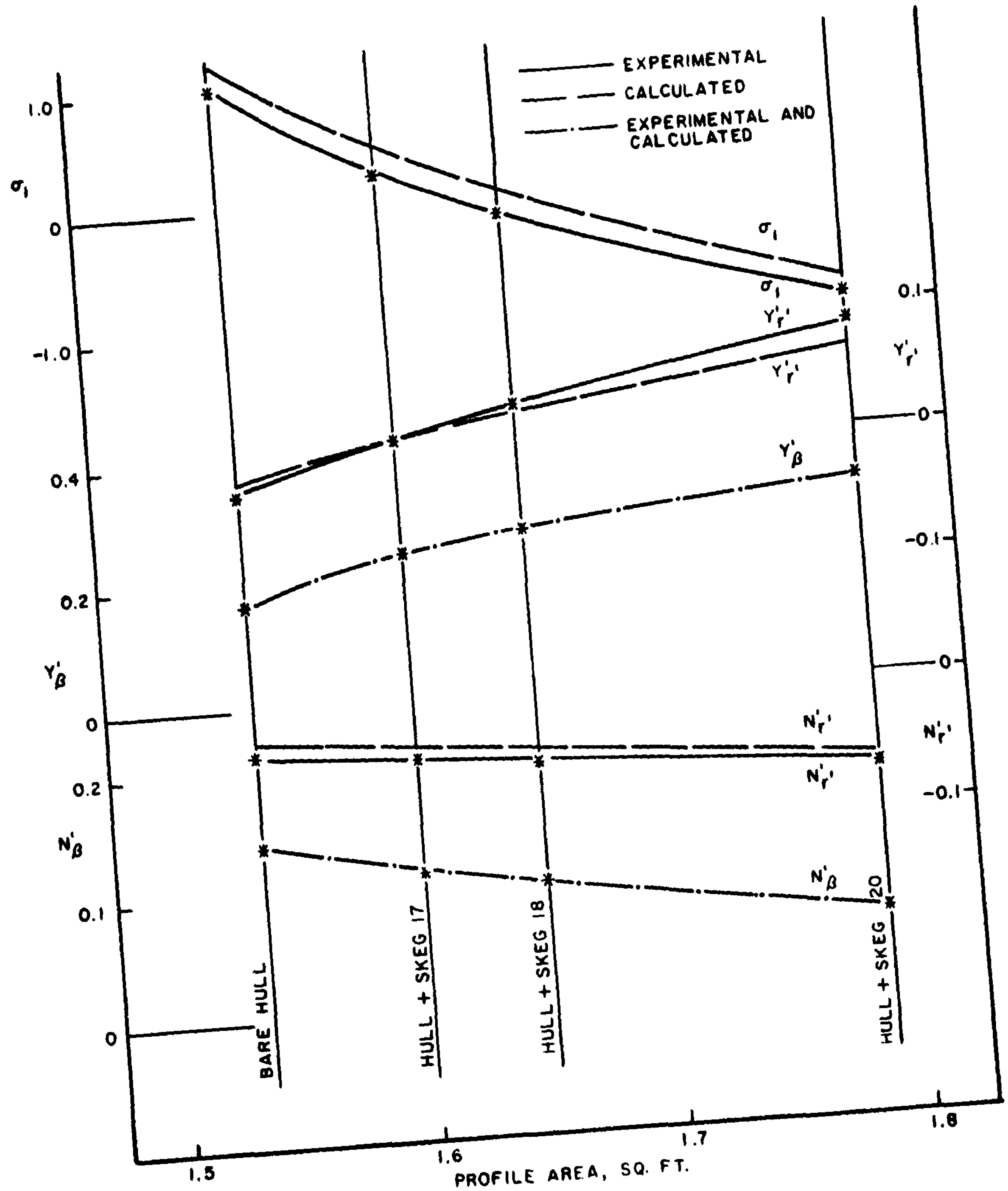


FIGURE 10. COMPARISON OF CALCULATED AND EXPERIMENTAL STABILITY DERIVATIVES AND INDICES FOR 842 HULL WITH VARIOUS SKEGS (1959 DATA) (R-740)

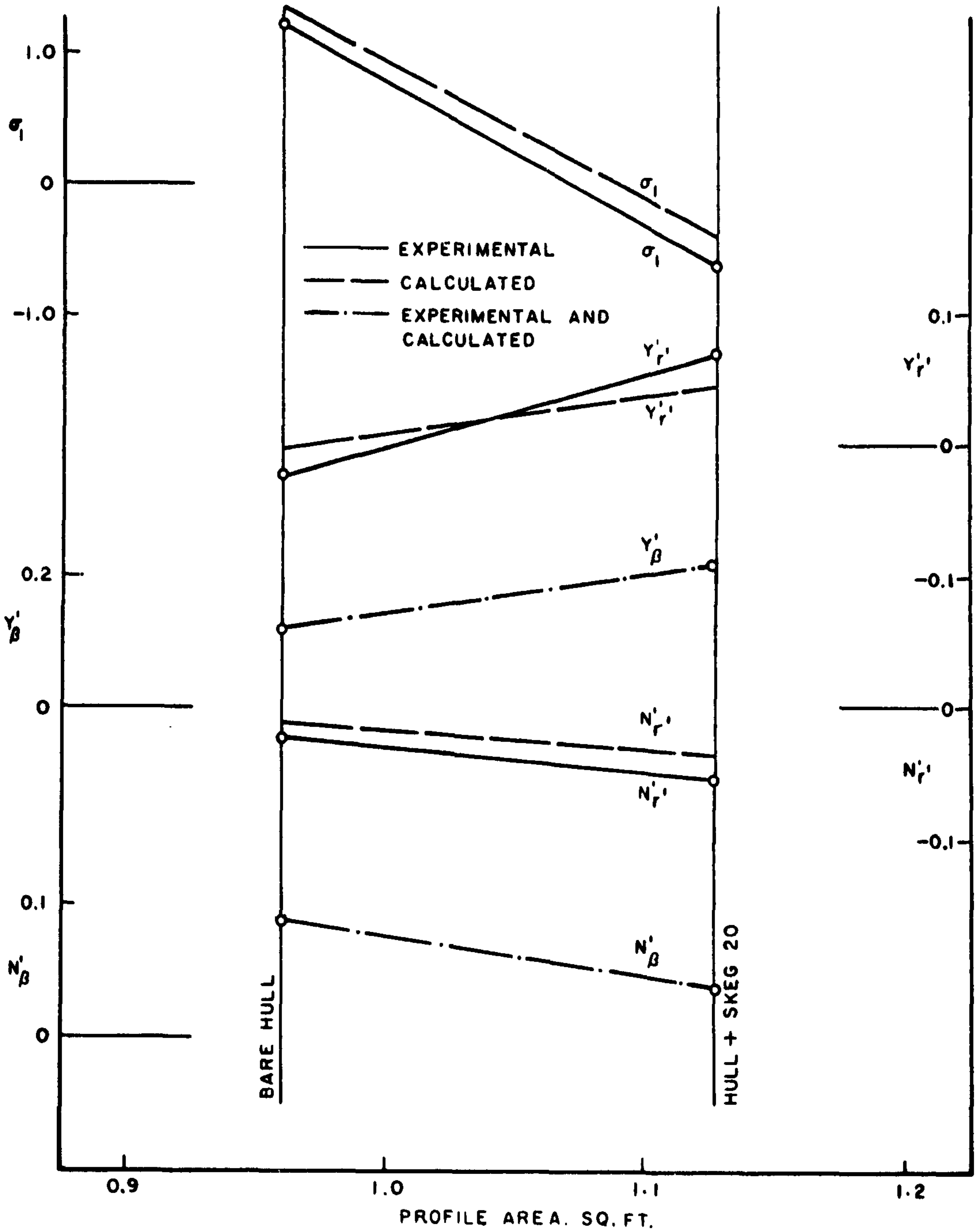


FIGURE 11. COMPARISON OF CALCULATED AND EXPERIMENTAL STABILITY DERIVATIVES AND INDICES FOR 846 HULL WITHOUT AND WITH SKEG (1951 DATA)

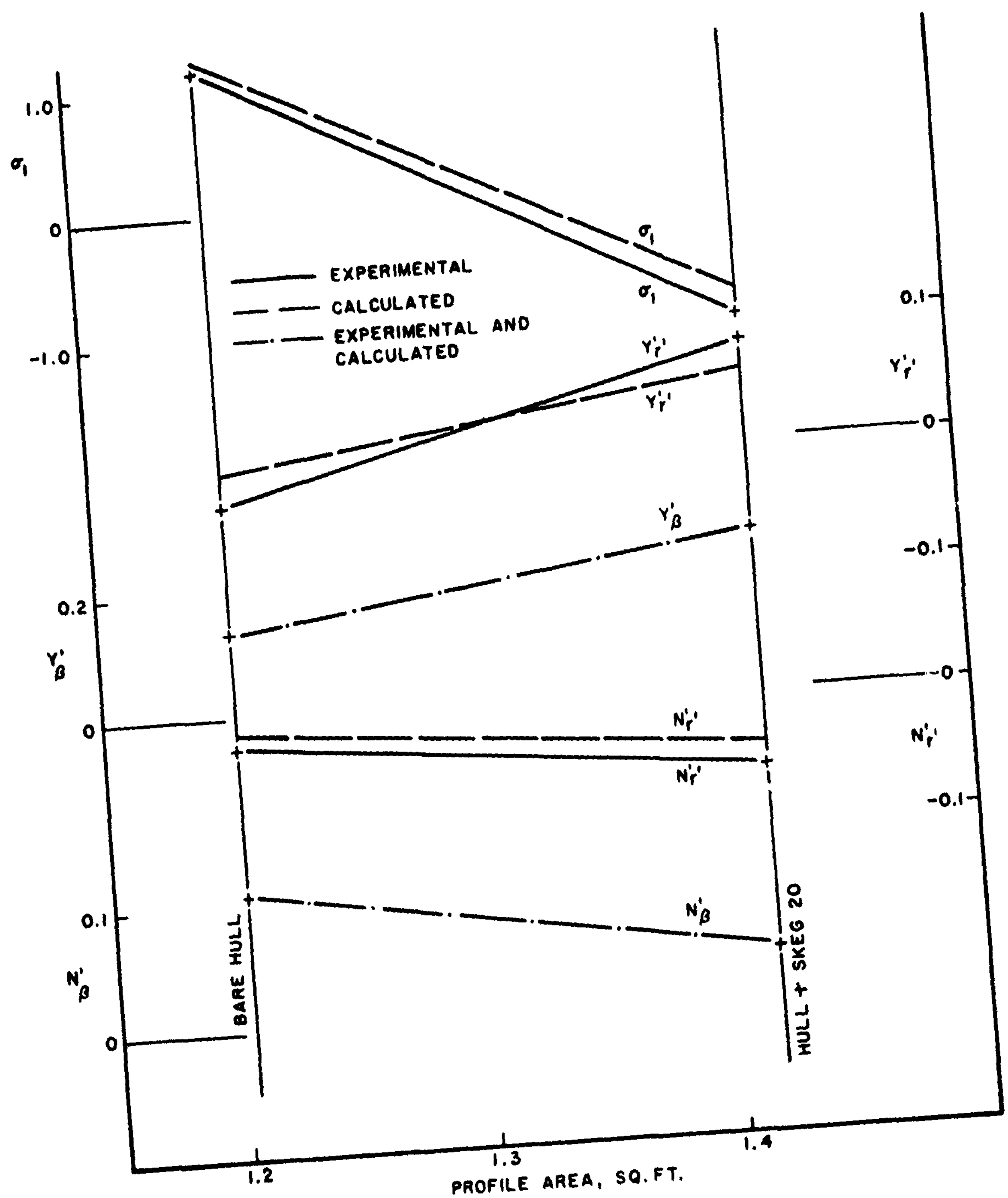


FIGURE 12. COMPARISON OF CALCULATED AND EXPERIMENTAL STABILITY DERIVATIVES AND INDICES FOR 848 HULL WITHOUT AND WITH SKEG (1951 DATA)

APPENDIX
DATA CHARTS

Figures A-1 to A-48

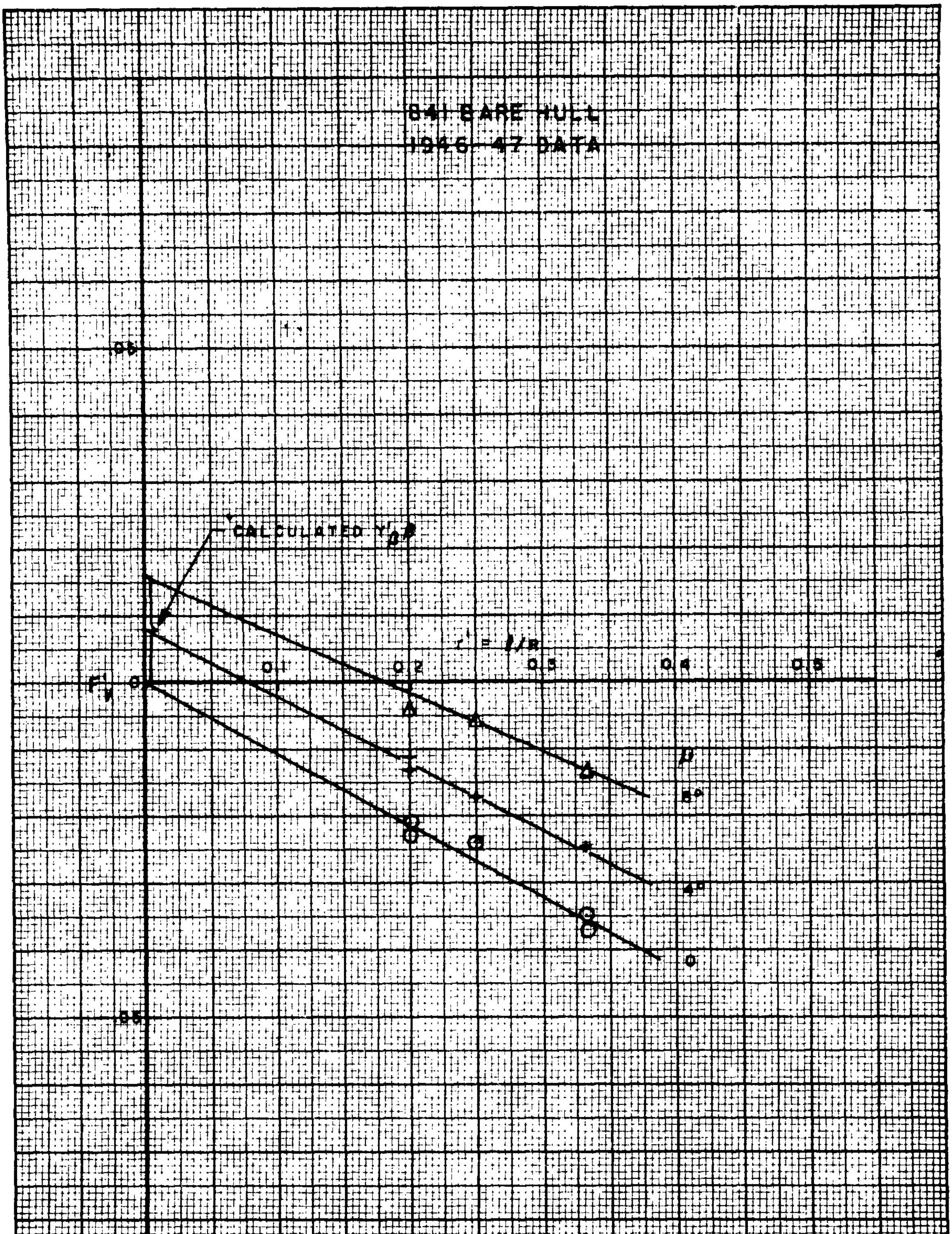


FIGURE A-1

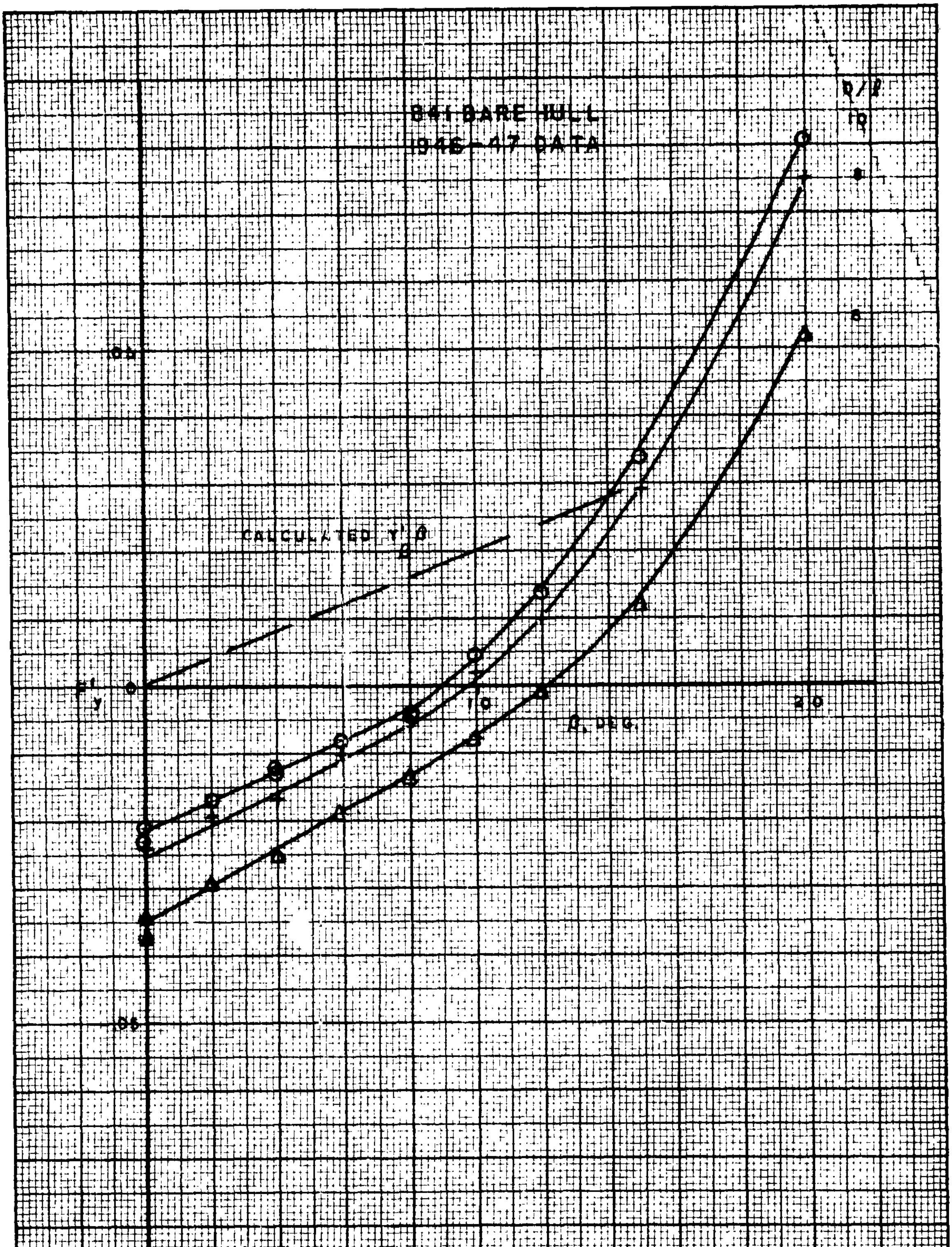

841 BARE HULL
1946-47 DATA
D/ℓ
10
8
6
CALCULATED Y'β
.05
-.05
10
20
β, DEG.

FIGURE A-2

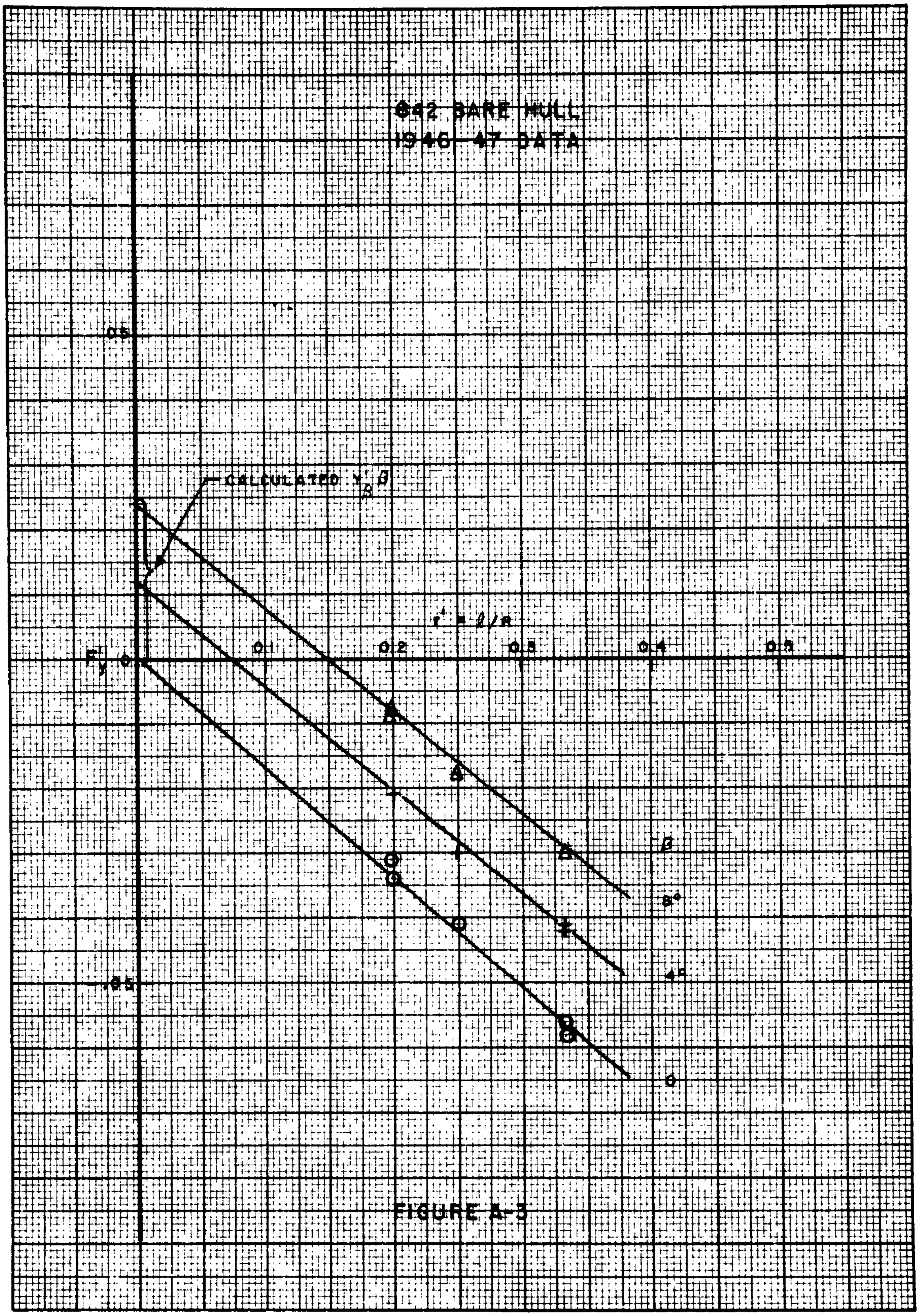
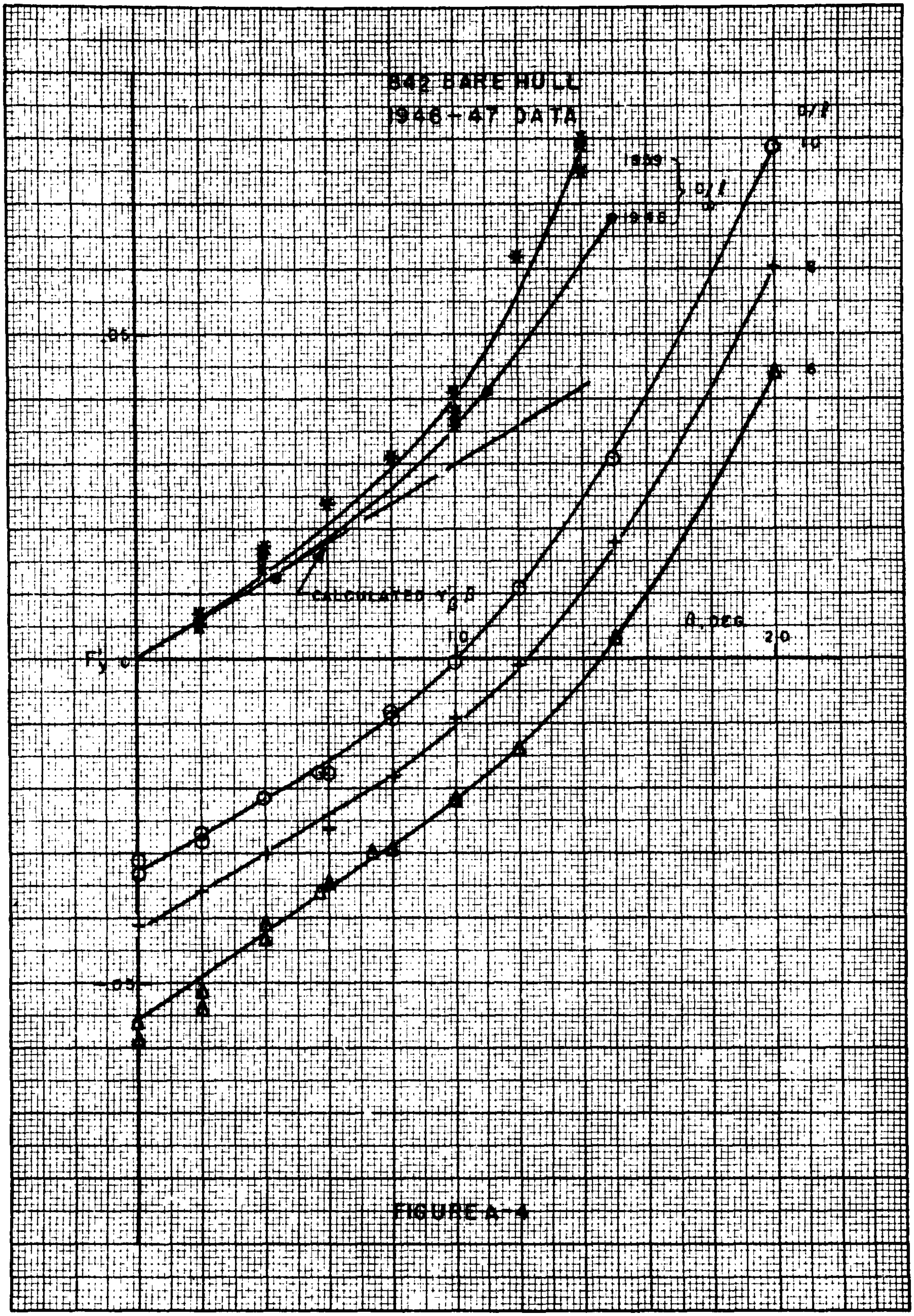
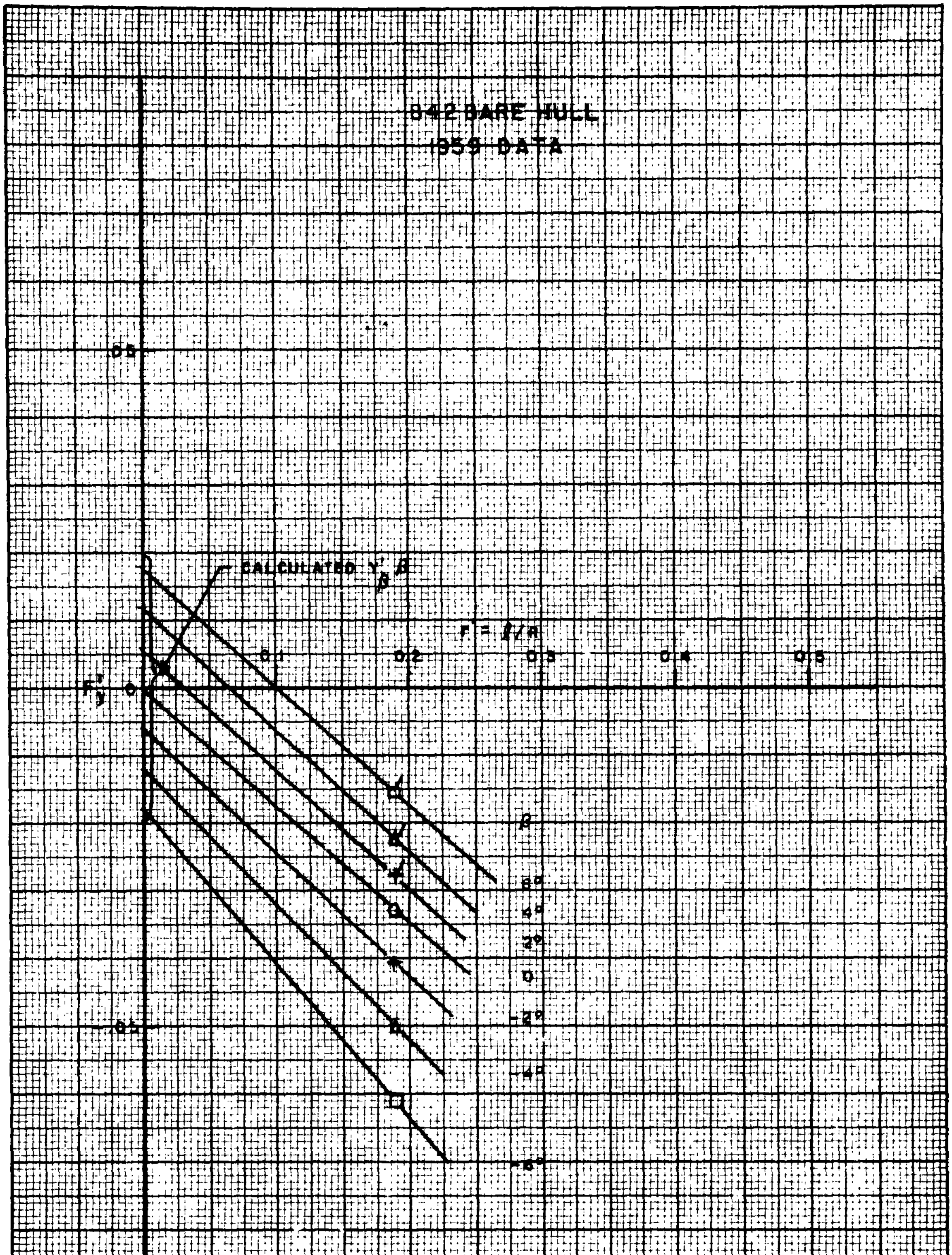

842 BARE HULL
1946-47 DATA
CALCULATED $Y_\beta \beta$
$r' = \ell/R$
.05
0
-.05
F'_y
0.1
0.2
0.3
0.4
0.5
β
8°
4°
0

FIGURE A-3



842 BARE HULL
1946-47 DATA
D/ℓ
10
8
6
1939
1946
D/ℓ
.05
CALCULATED Y'β β
1.0
β, DEG
2.0
-.05

FIGURE A-4



842 BARE HULL
1959 DATA
CALCULATED Y'_β
$r' = \ell/R$
0.1
0.2
0.3
0.4
0.5
.05
F'_y 0
-.05
β
6°
4°
2°
0
-2°
-4°
-6°

FIGURE A-5

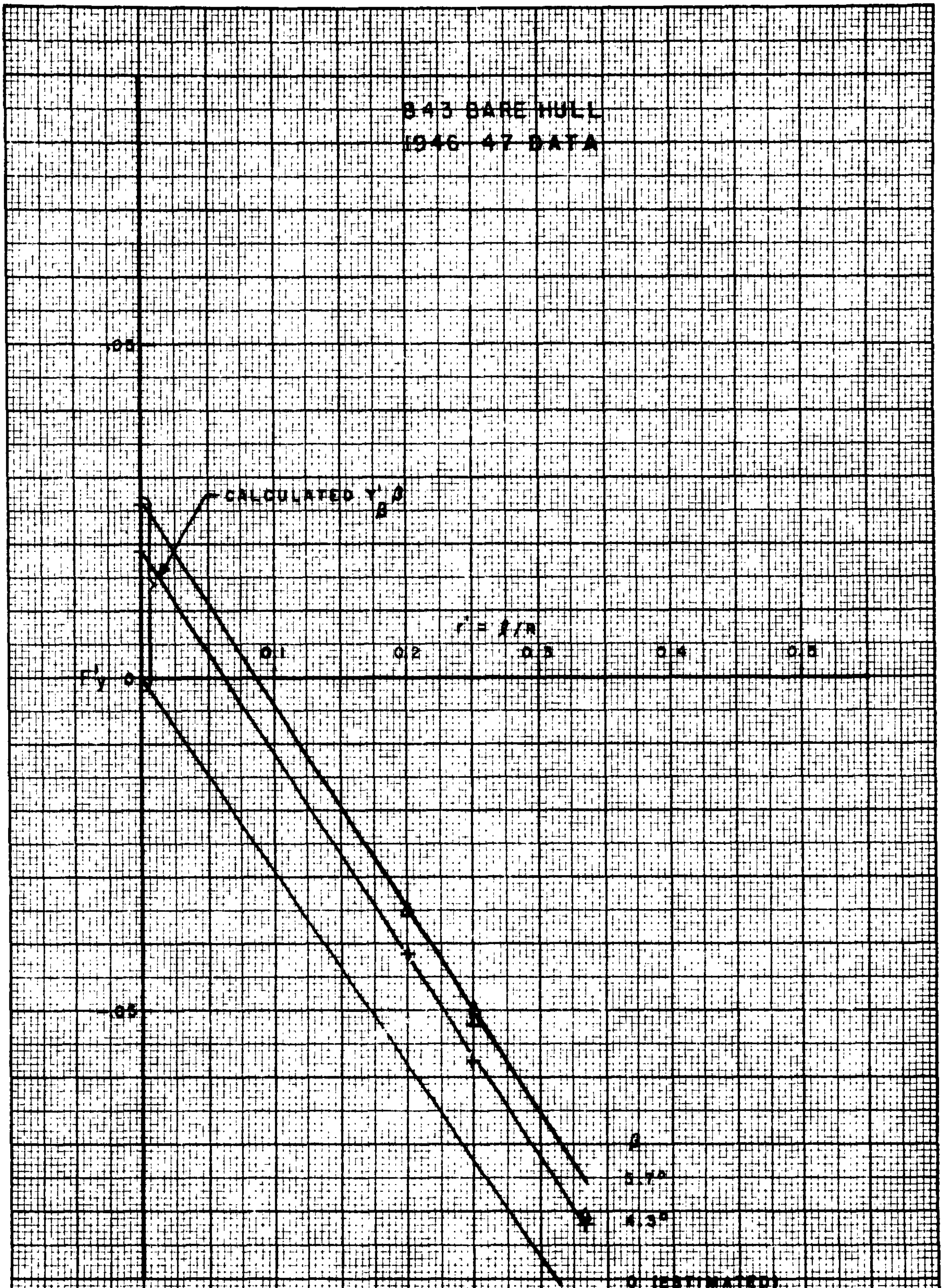

B43 BARE HULL
1946 47 DATA
CALCULATED Y'β β
.05
0.1
0.2
0.3
0.4
0.5
Y'r 0
-.05
β
5.7°
4.3°
0 (ESTIMATED)

FIGURE A-6

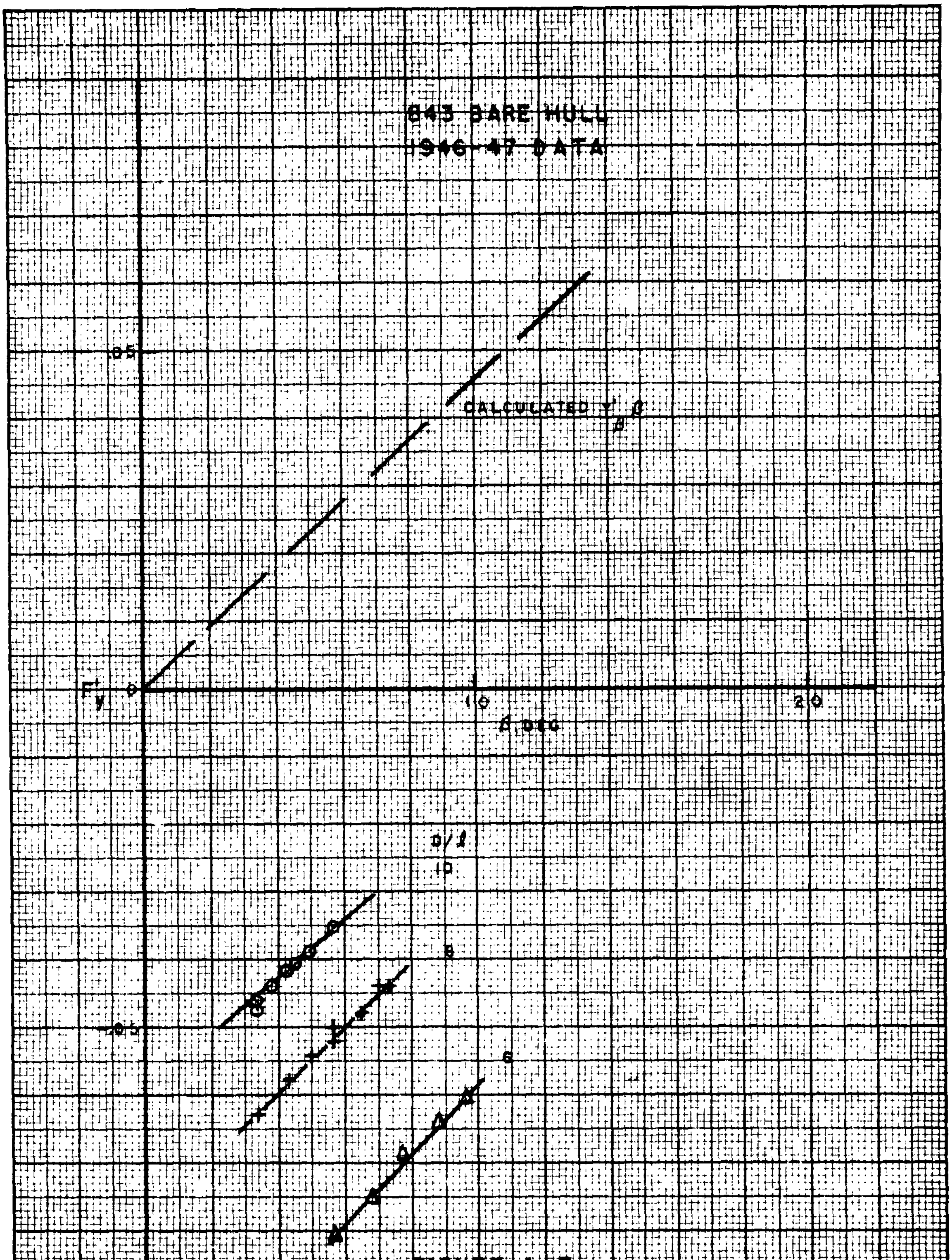

643 BARE HULL
1946-47 DATA
.05
CALCULATED Y'β
0
10
20
β, DEG
D/ℓ
10
8
6
-.05

FIGURE A-7

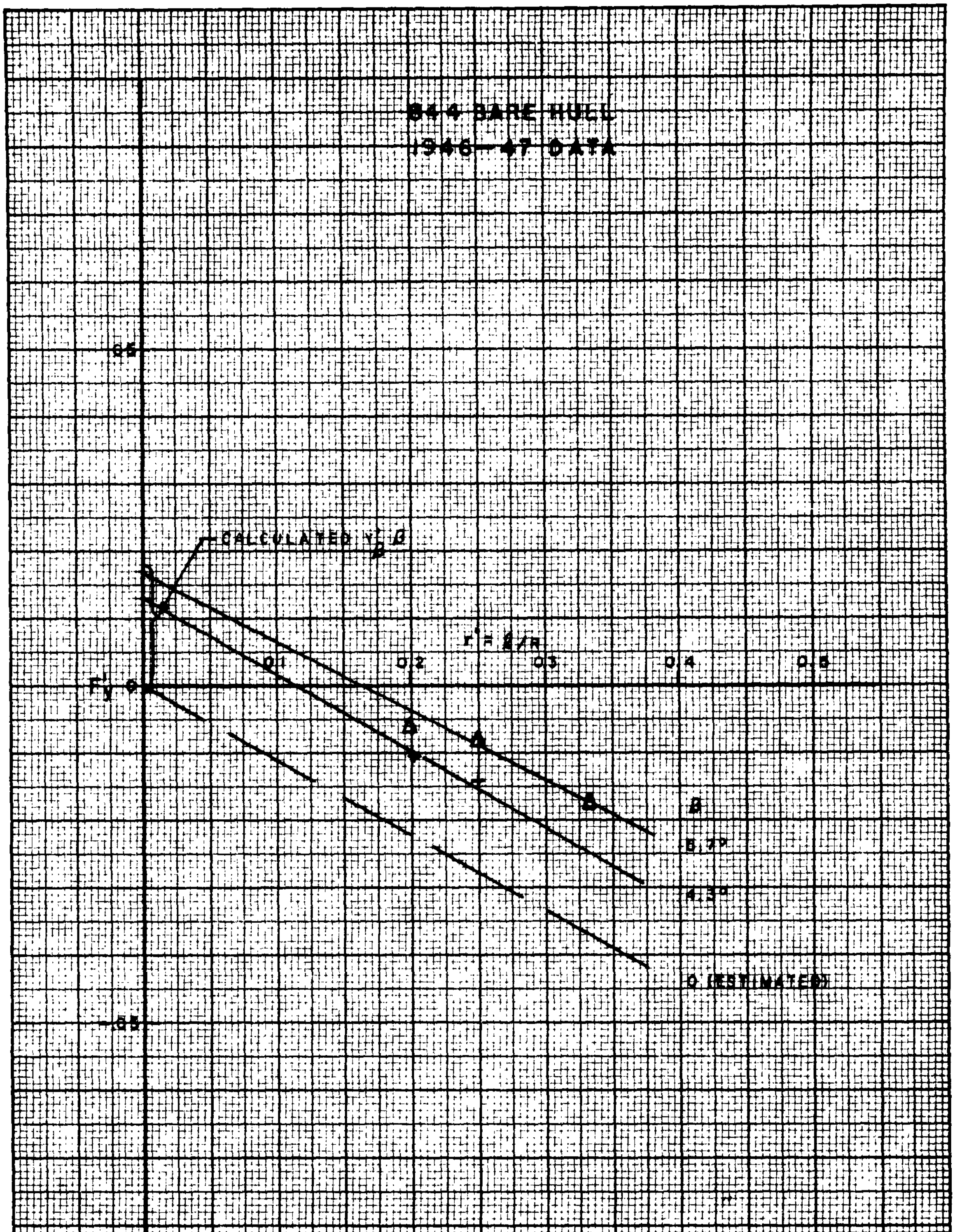

844 BARE HULL
1946—47 DATA
.05
CALCULATED Y'_β
$r' = \dot{\psi}l/u$
0.1
0.2
0.3
0.4
0.5
F'_y 0
β
5.7°
4.3°
0 (ESTIMATED)
-.05

FIGURE A-8

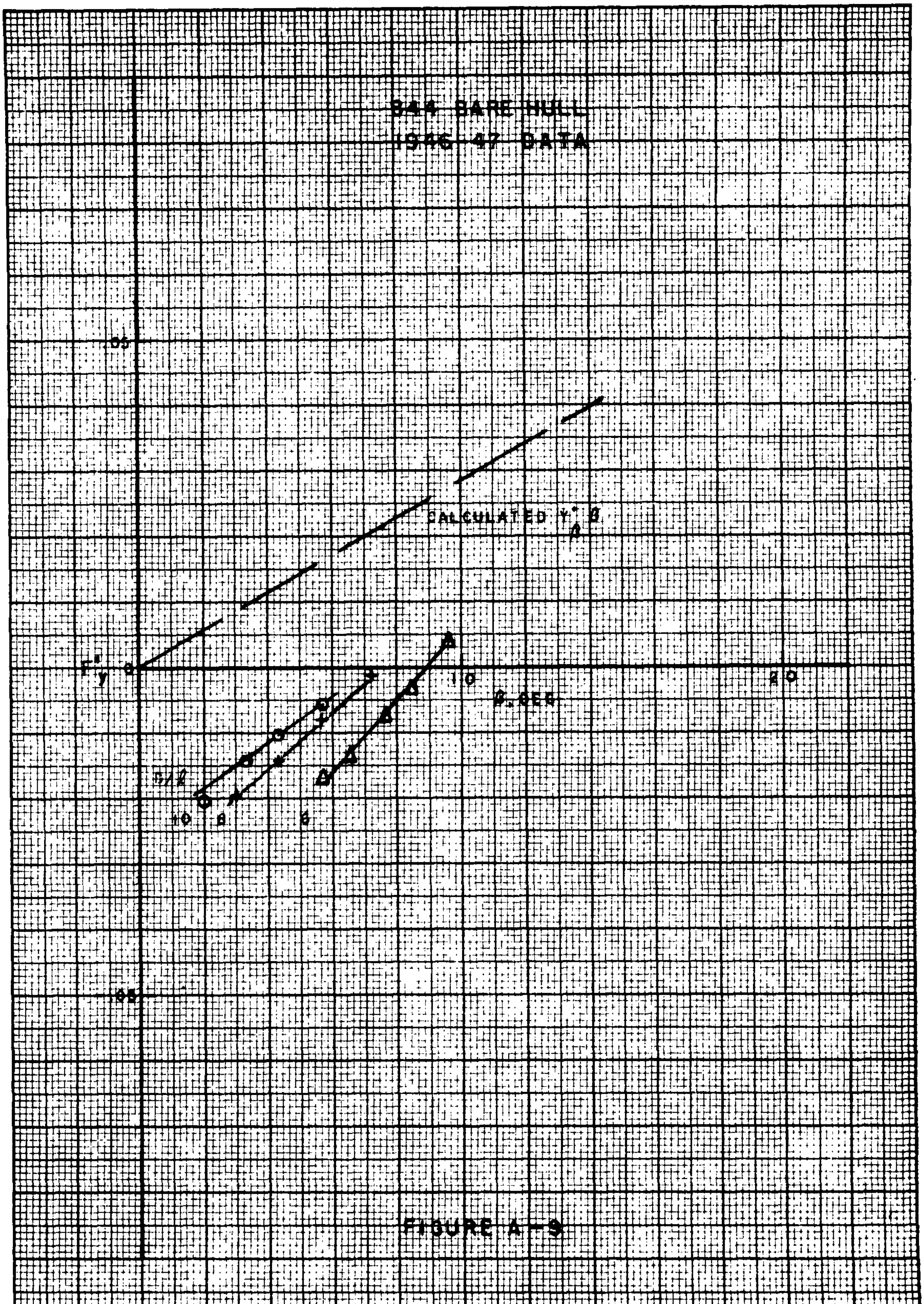
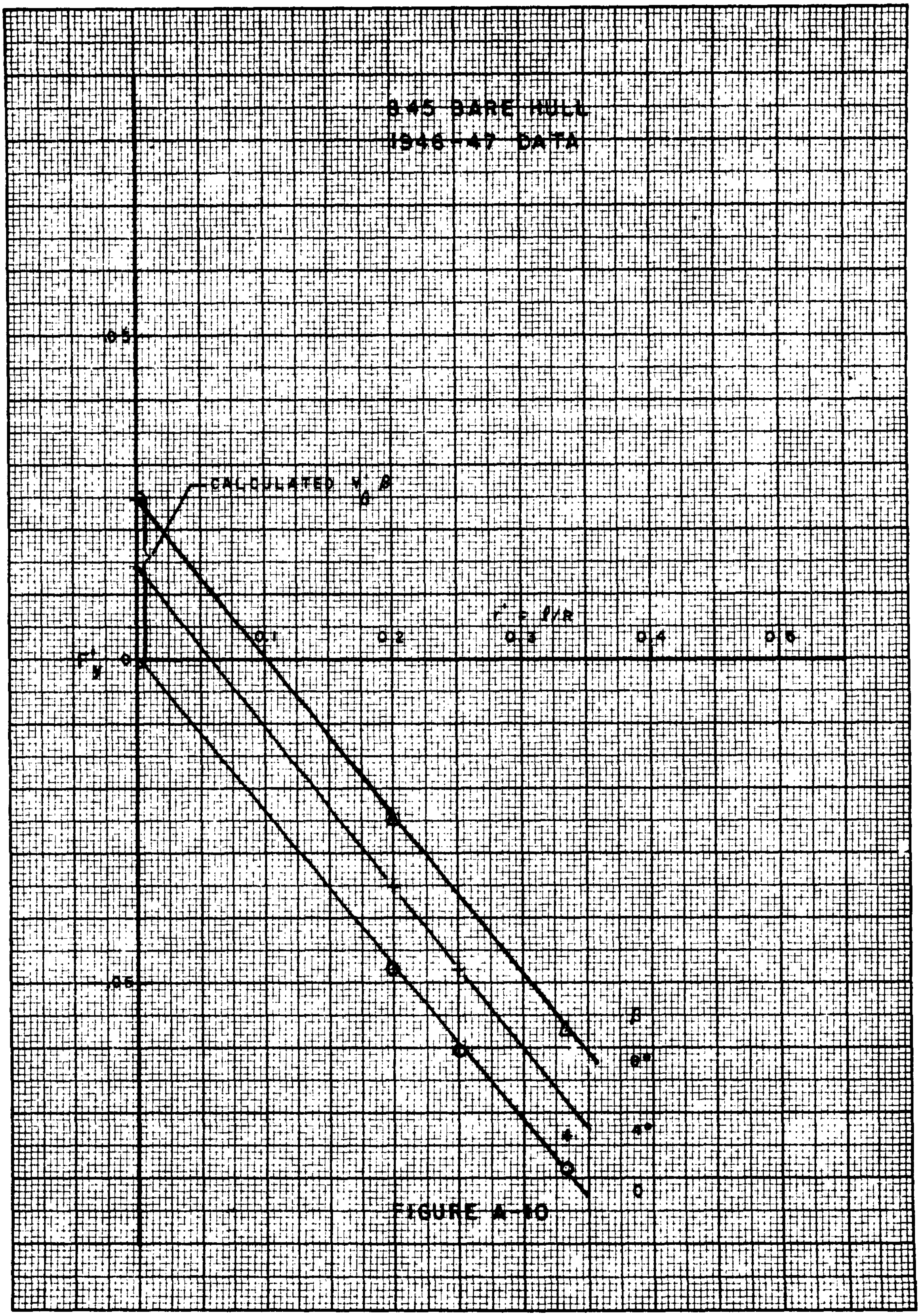

844 BARE HULL
1946-47 DATA
CALCULATED $Y'_\beta \beta$
.05
F'_y
0
10
20
β, DEG.
.05
10
8
6

FIGURE A-9


845 BARE HULL
1946-47 DATA
CALCULATED
.05
0.1
0.2
0.3
0.4
0.5
-.05
8°
4°
0
FIGURE A-20

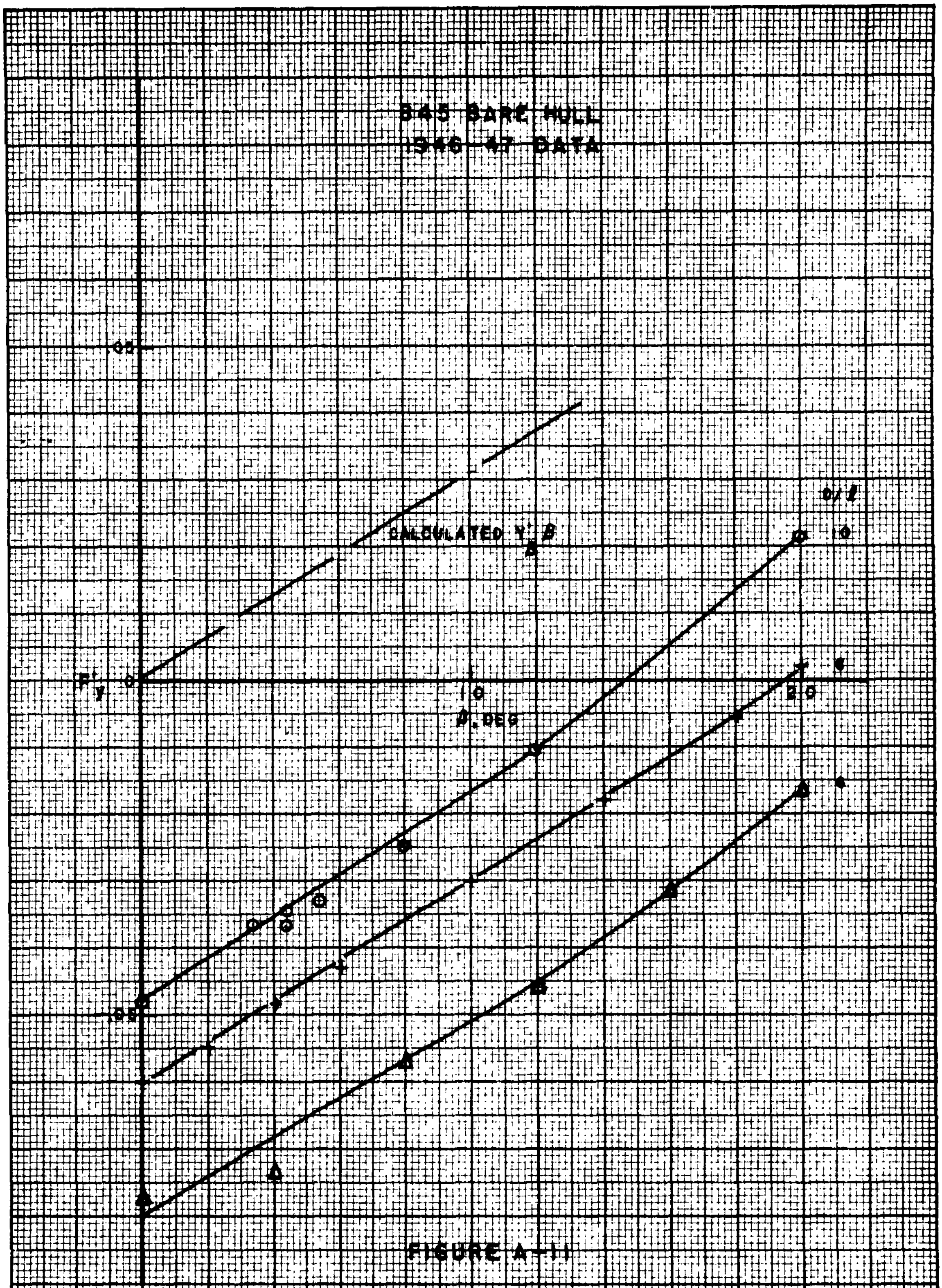
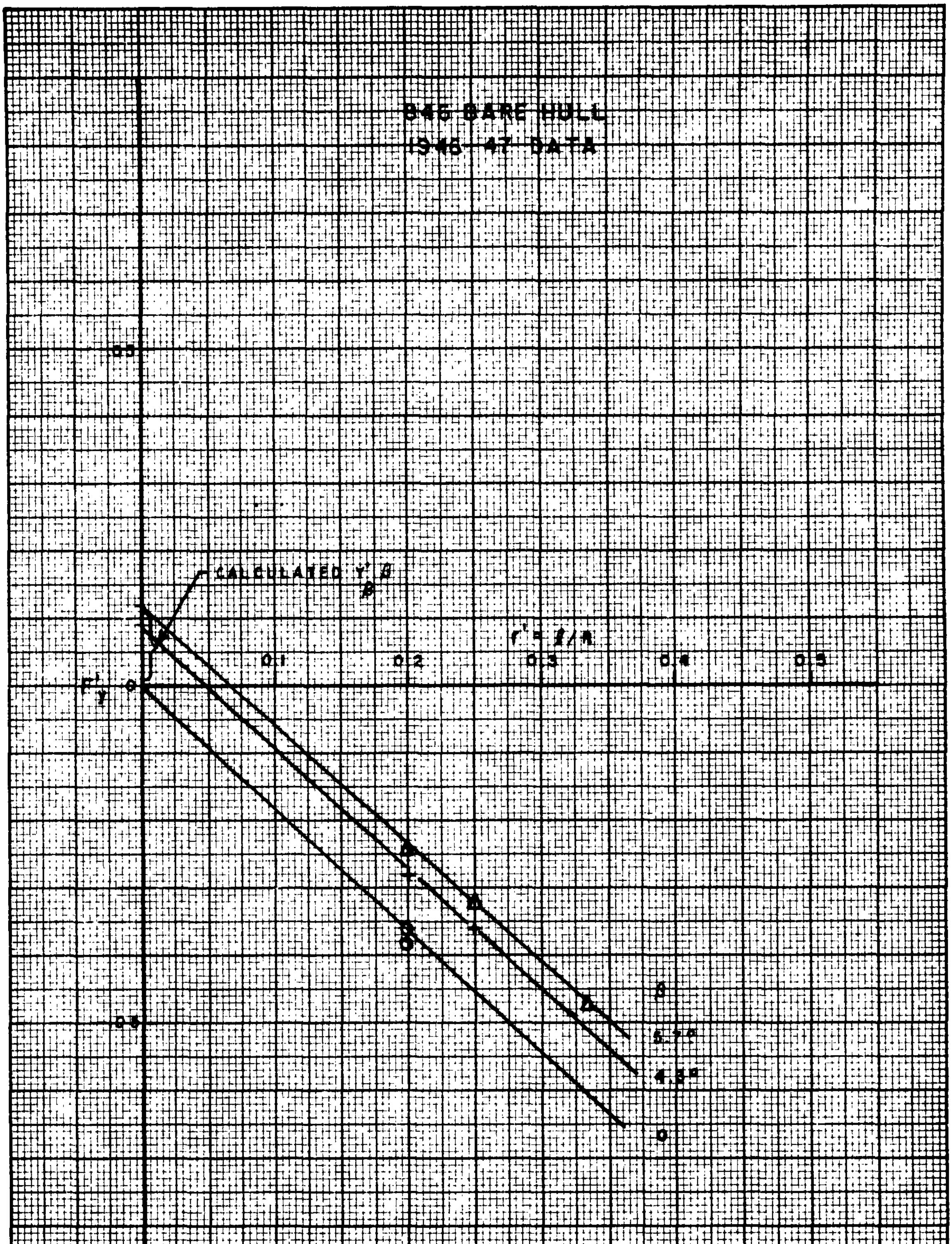


FIGURE A-11



B46 BARE HULL
1946–47 DATA
CALCULATED $Y'_\beta \beta$
$r' = l/R$
0.1
0.2
0.3
0.4
0.5
Y'_r
0
β
5.7°
4.3°
0

FIGURE A-12

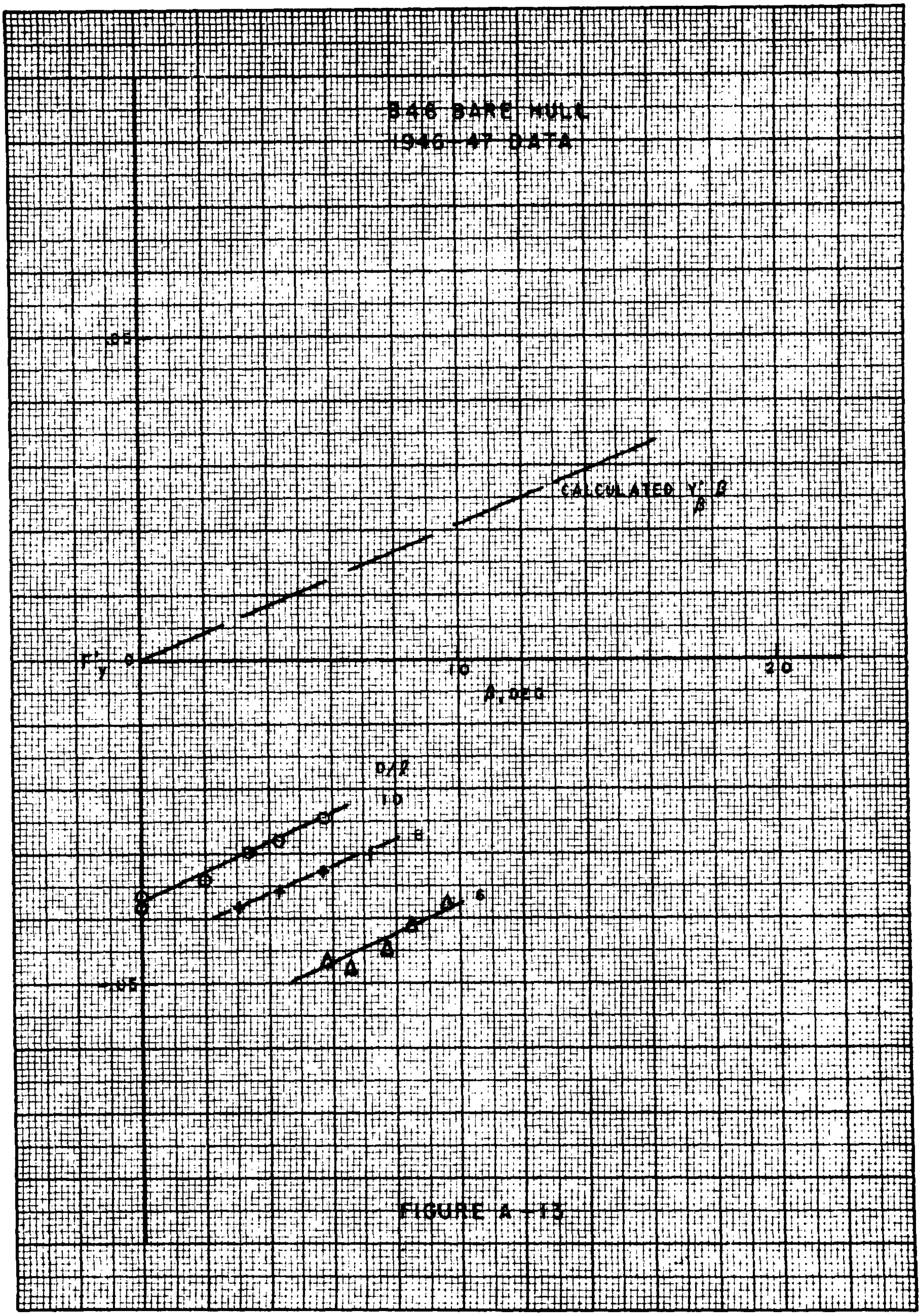
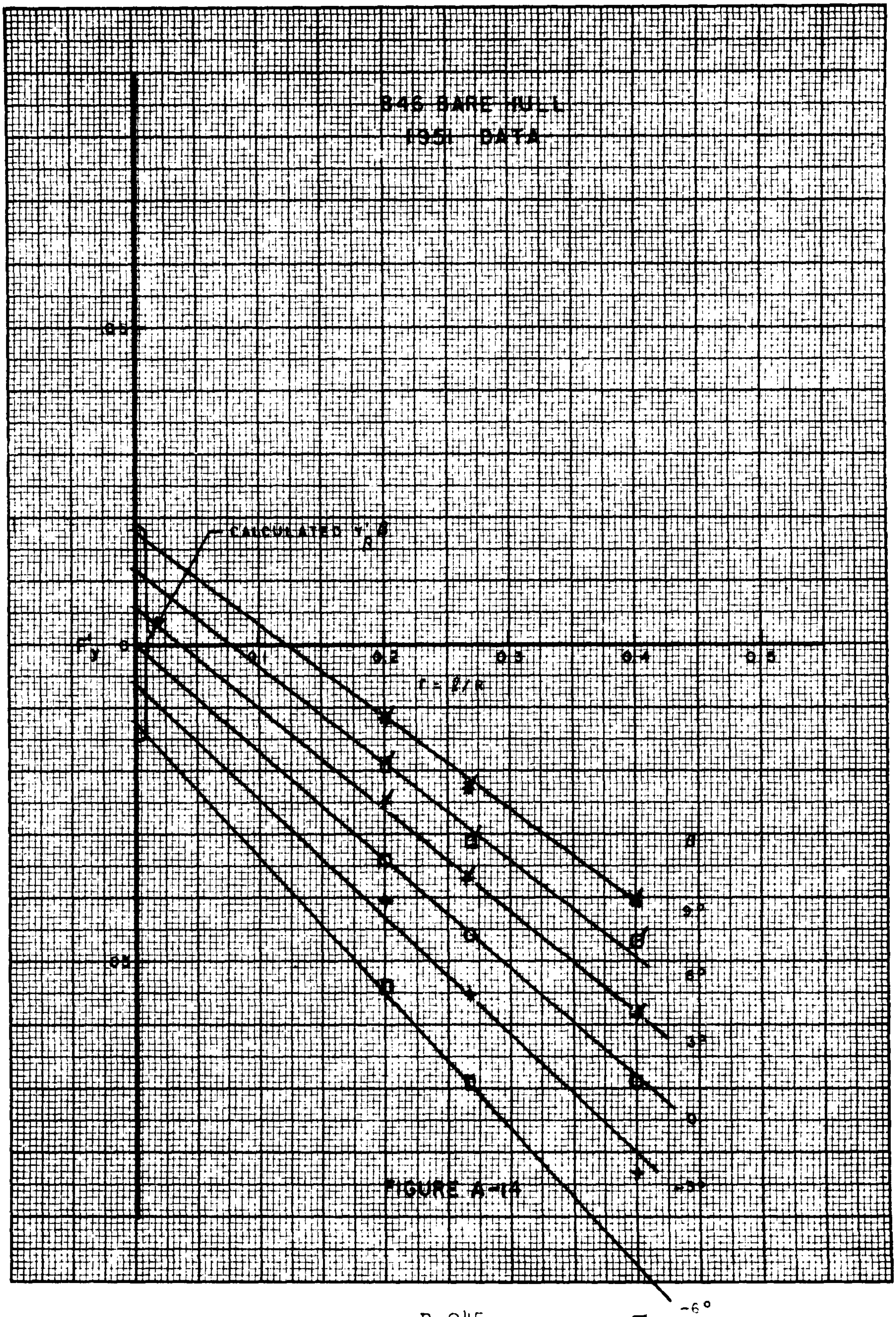
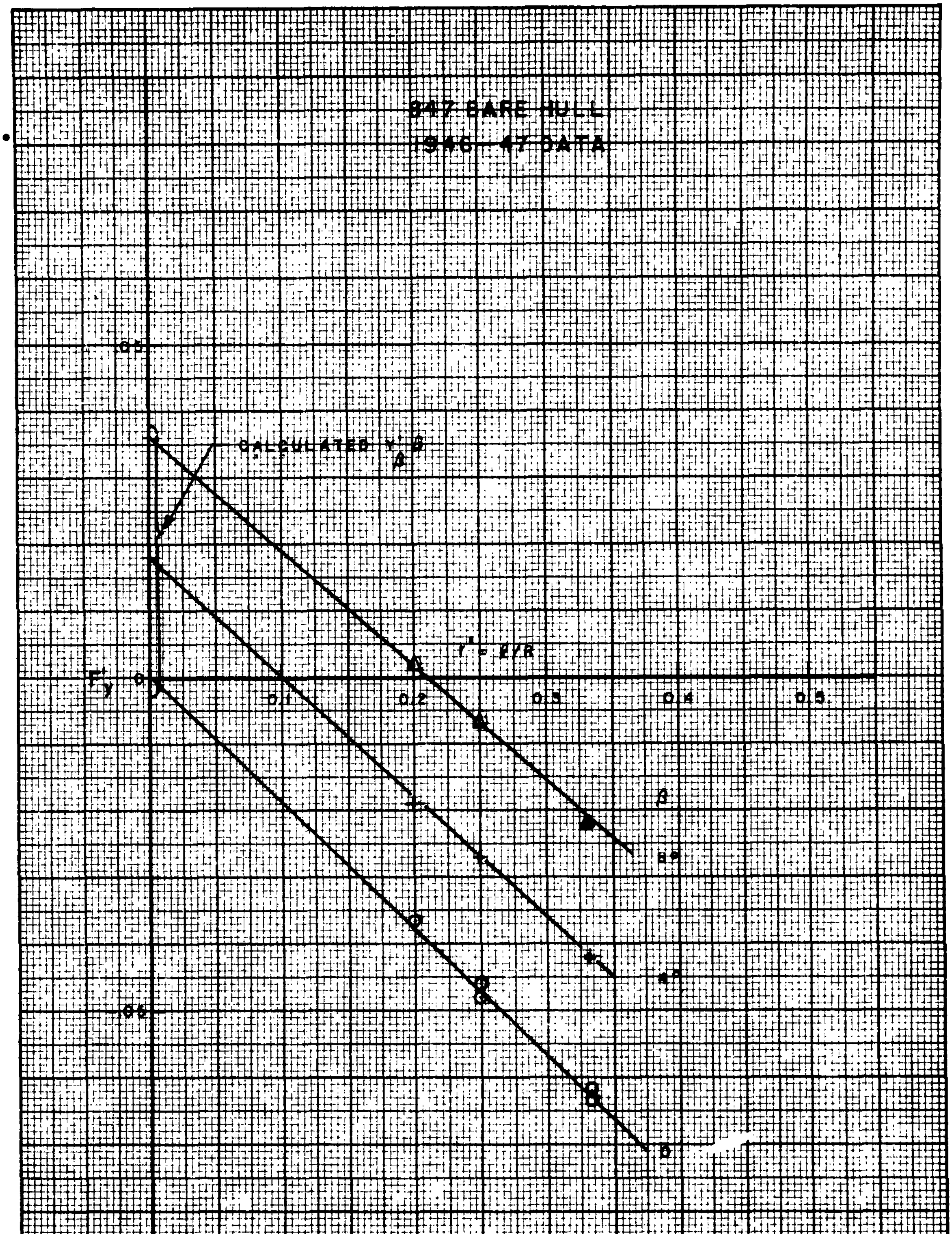

B46 BARE HULL
1946-47 DATA
.05
-.05
0
1.0
2.0
β, DEG
CALCULATED
D/ℓ
10
8
6

FIGURE A-13



846 BARE HULL
1951 DATA
CALCULATED
.1
.2
.3
.4
.5
9°
6°
3°
0
-3°
-6°
FIGURE A-14



847 BARE HULL
1946 - 47 DATA
.05
CALCULATED Y'_β
$r' = 2Y/R$
F_y
0
0.1
0.2
0.3
0.4
0.5
-.05

FIGURE A-15

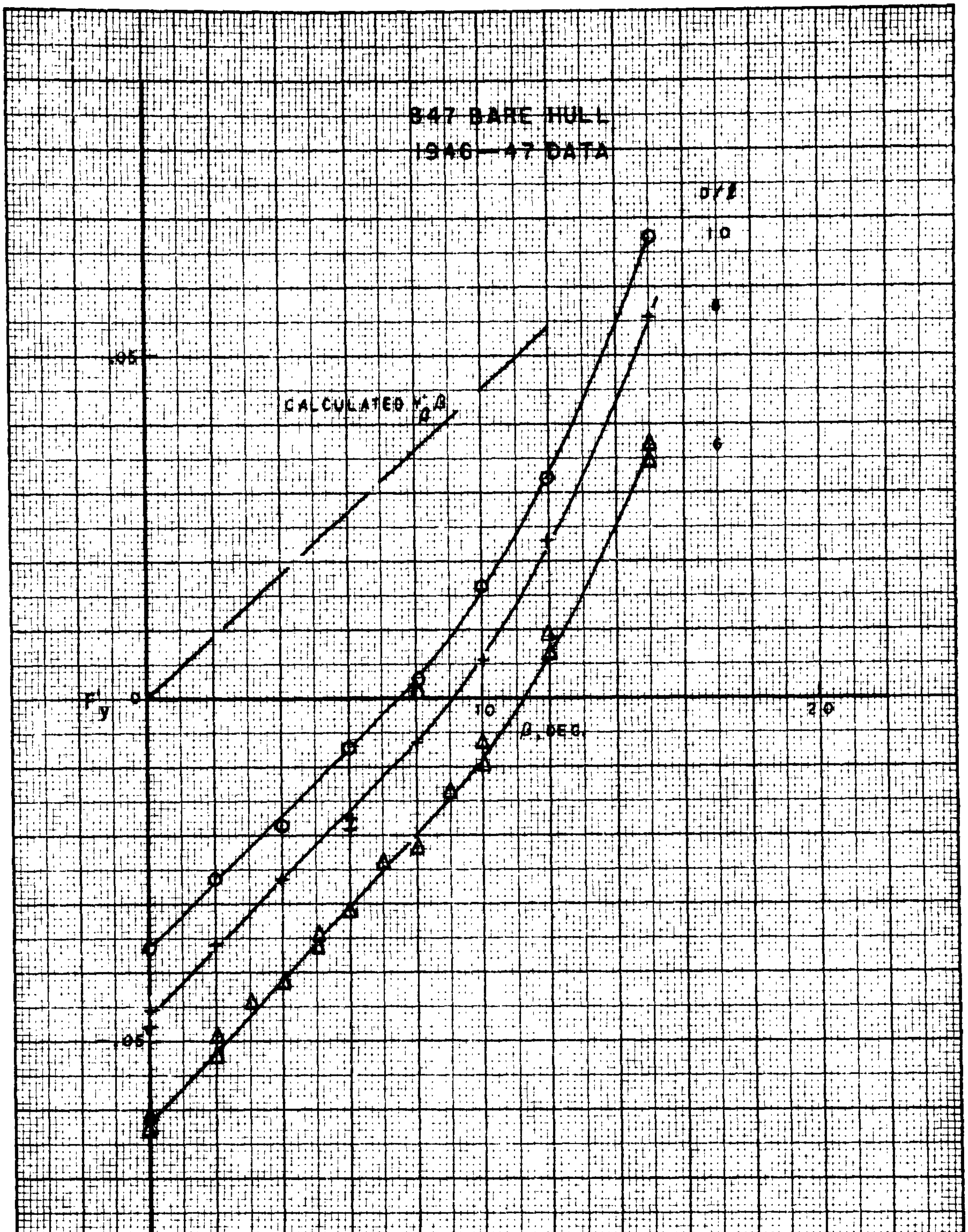
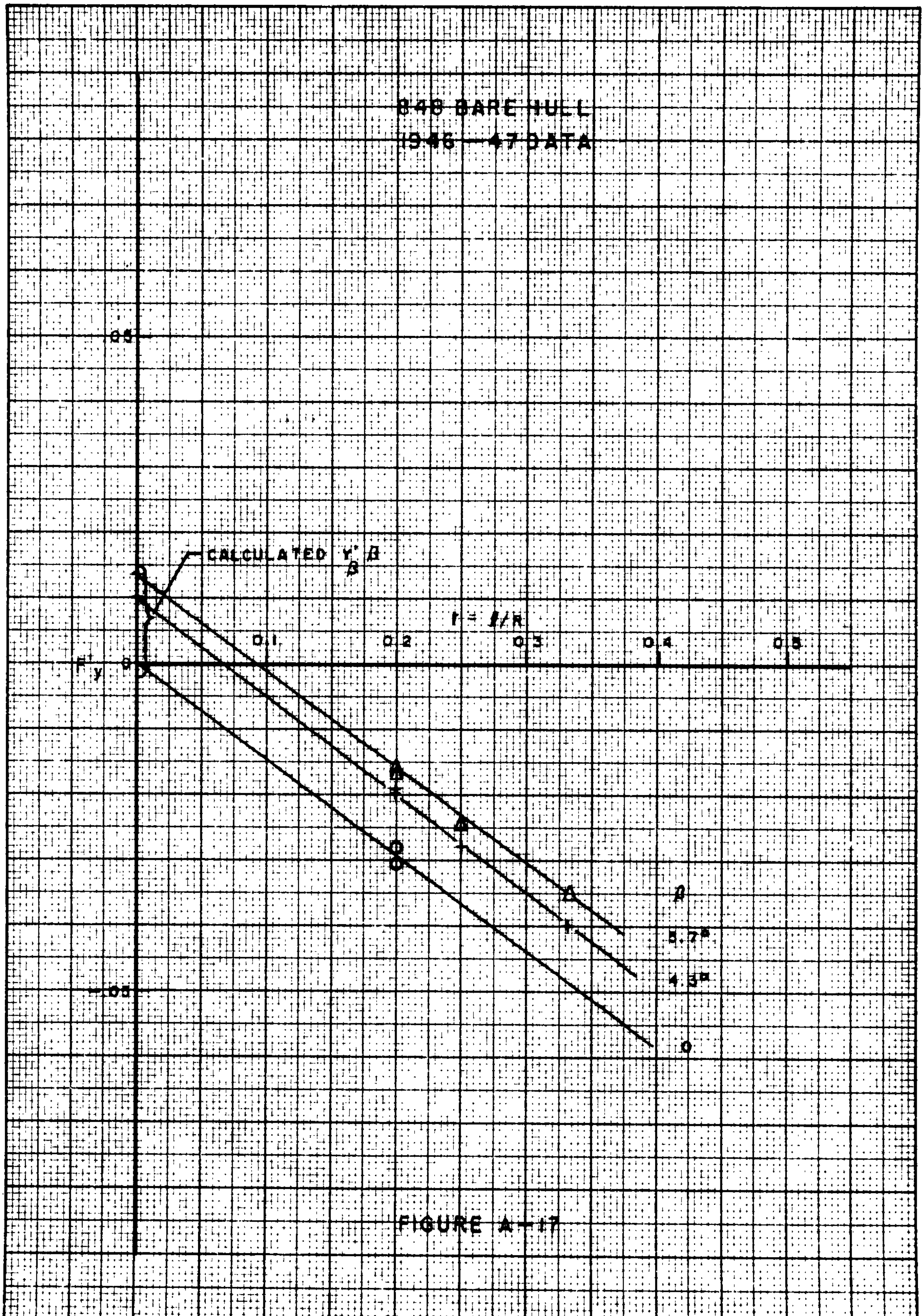

847 BARE HULL
1946—47 DATA
D/ℓ
10
8
6
.05
CALCULATED $Y'_{\beta}\beta$
F'_y
0
10
20
β, DEG.
.05

FIGURE A-16



848 BARE HULL
1946 — 47 DATA
CALCULATED Y'_β
$r = \ell/R$
.05
0
-.05
F'_y
0.1
0.2
0.3
0.4
0.5
β
5.7°
4.3°
0

FIGURE A-17

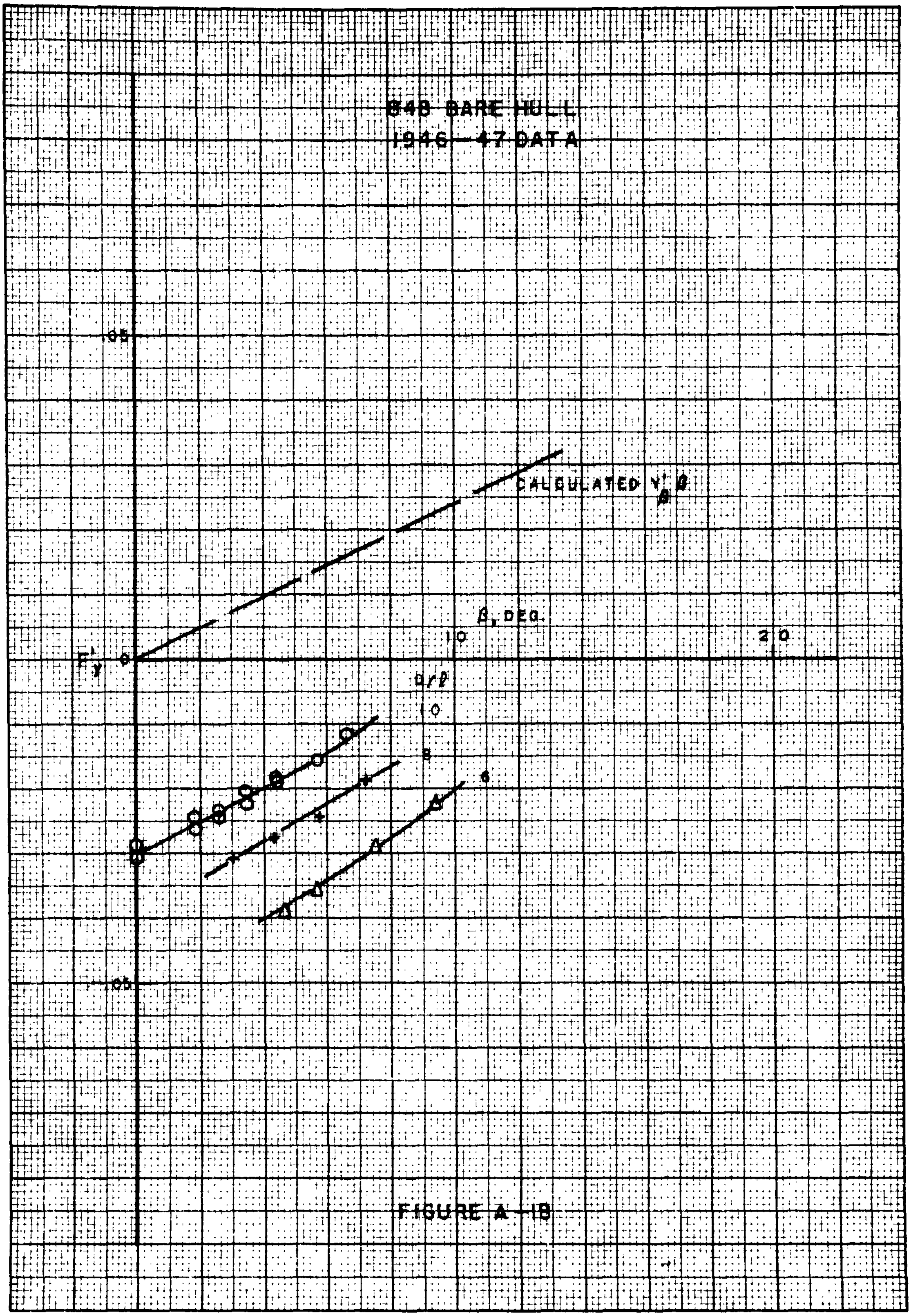

848 BARE HULL
1946—47 DATA
CALCULATED $Y'_\beta \beta$
β, DEG.
10
20
.05
F'_y
0
-.05
b/ℓ
1.0
.8
.6

FIGURE A-1B

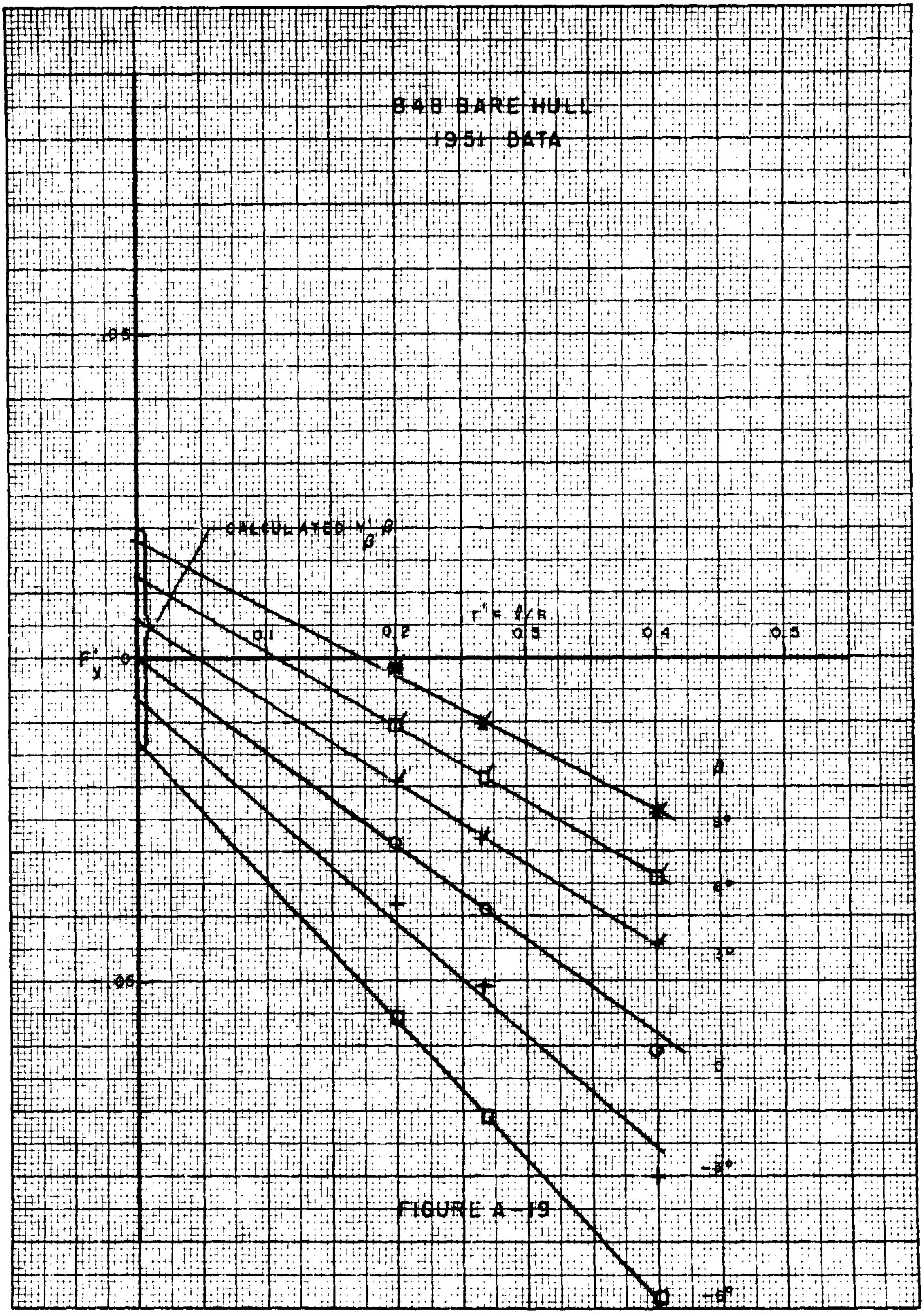
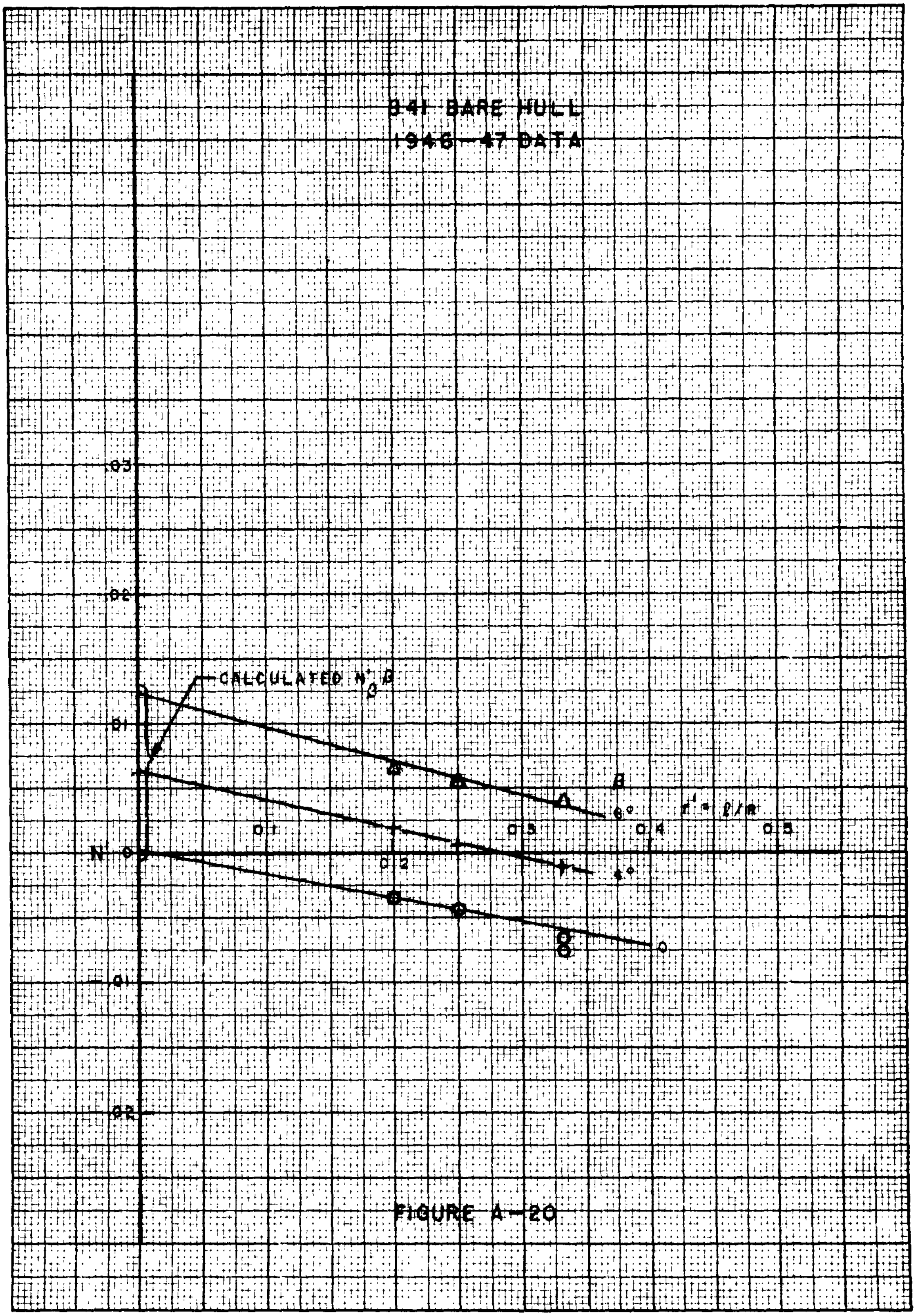

848 BARE HULL
1951 DATA
CALCULATED $Y'_\beta \beta$
$r' = \ell/R$
.1
.2
.3
.4
.5
.05
0
-.05
F'_y
β
9°
6°
3°
0
-3°
-6°

FIGURE A-19



B41 BARE HULL
1946–47 DATA
CALCULATED N'_β
.03
.02
.01
N
0
.01
.02
0.1
0.2
0.3
0.4
0.5
$r' = l/R$
8°
4°
0

FIGURE A–20

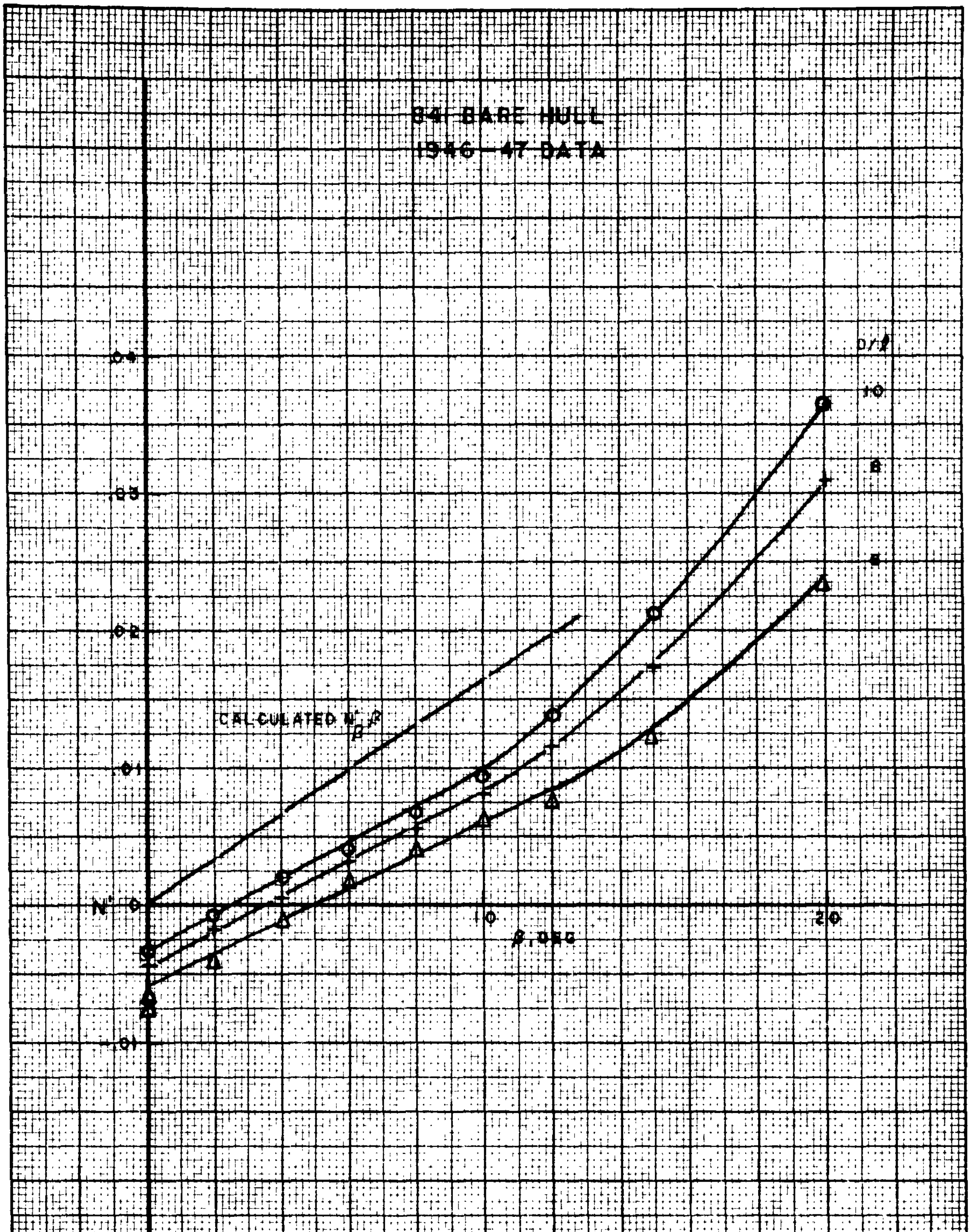

841 BARE HULL
1946 – 47 DATA
D/ℓ
10
8
6
.04
.03
.02
.01
N'
0
-.01
10
20
β, DEG
CALCULATED N'β β

FIGURE A – 21

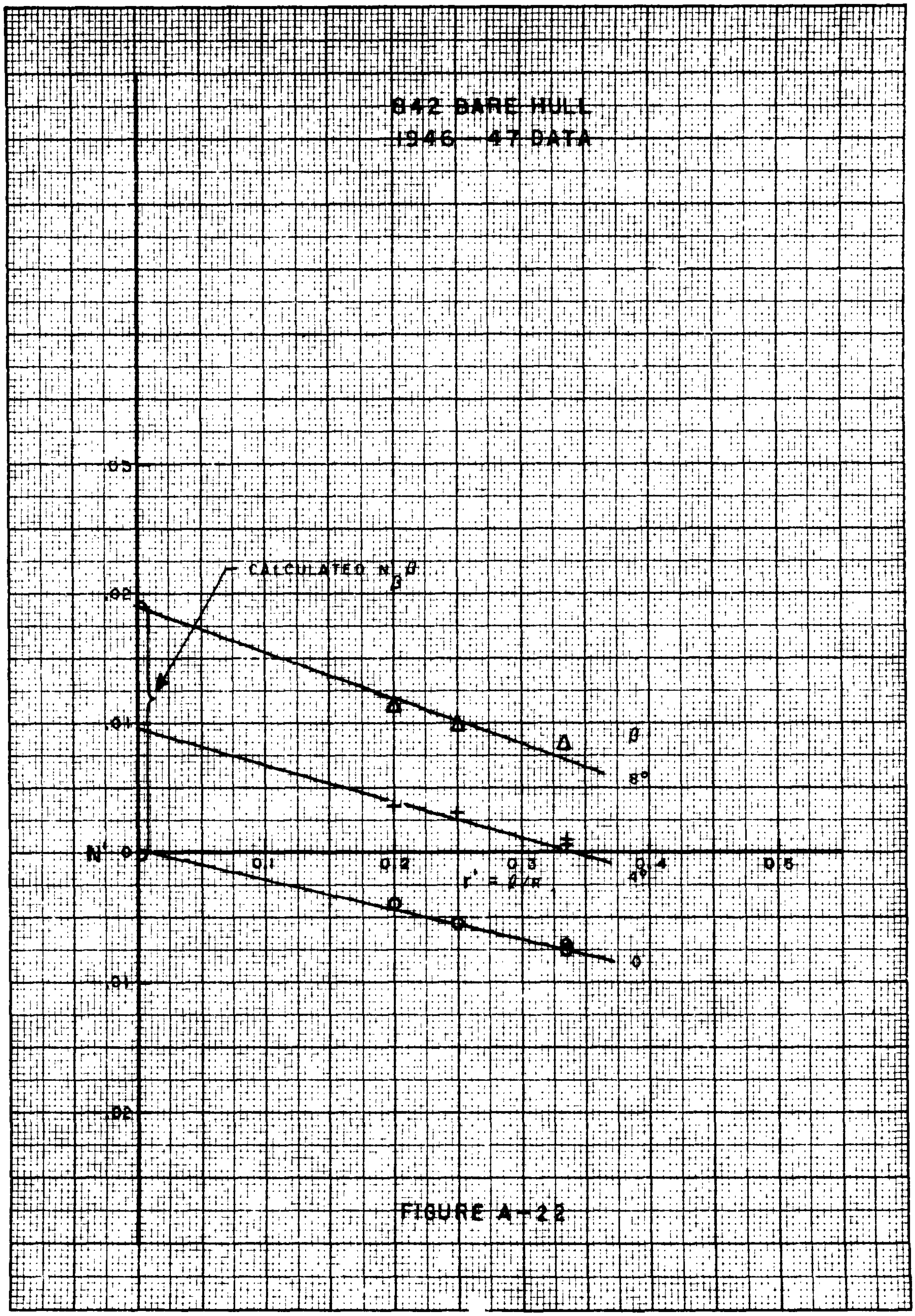

842 BARE HULL
1946 - 47 DATA
CALCULATED N_β
β
8°
4°
0
N'
r' = ψ/R
.03
.02
.01
0
.01
.02
0.1
0.2
0.3
0.4
0.5

FIGURE A-22

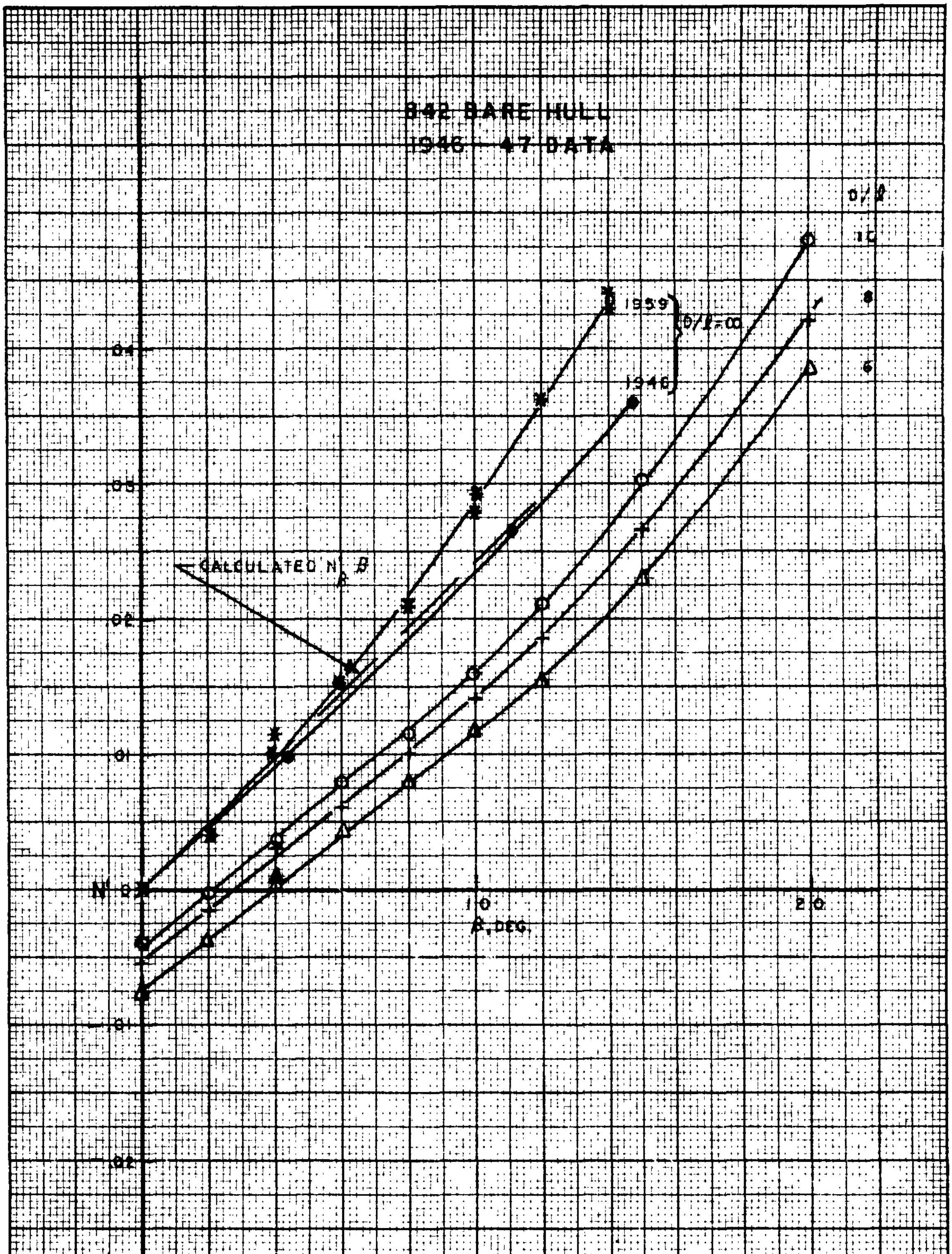
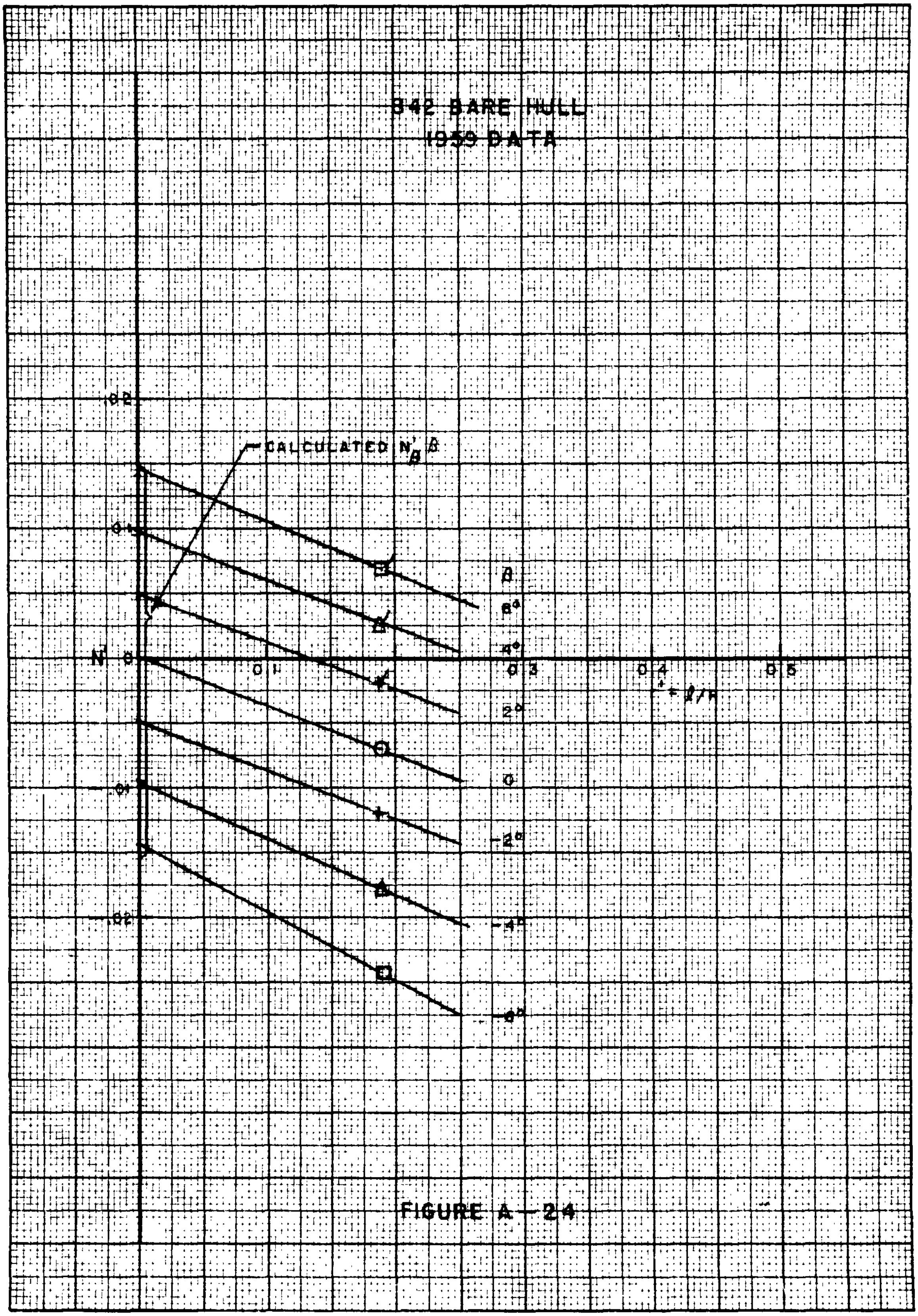

842 BARE HULL
1946 - 47 DATA
D/ℓ
10
8
6
1959
1946
D/ℓ = ∞
CALCULATED N'β β
.04
.03
.02
.01
N' 0
-.01
-.02
1.0
2.0
β, DEG.

FIGURE A-23



B42 BARE HULL
1959 DATA
CALCULATED $N'_\beta \beta$
β
6°
4°
2°
0
-2°
-4°
-6°
N'
.02
.01
0
-.01
-.02
0.1
0.3
0.4
0.5
ℓ/r

FIGURE A-24

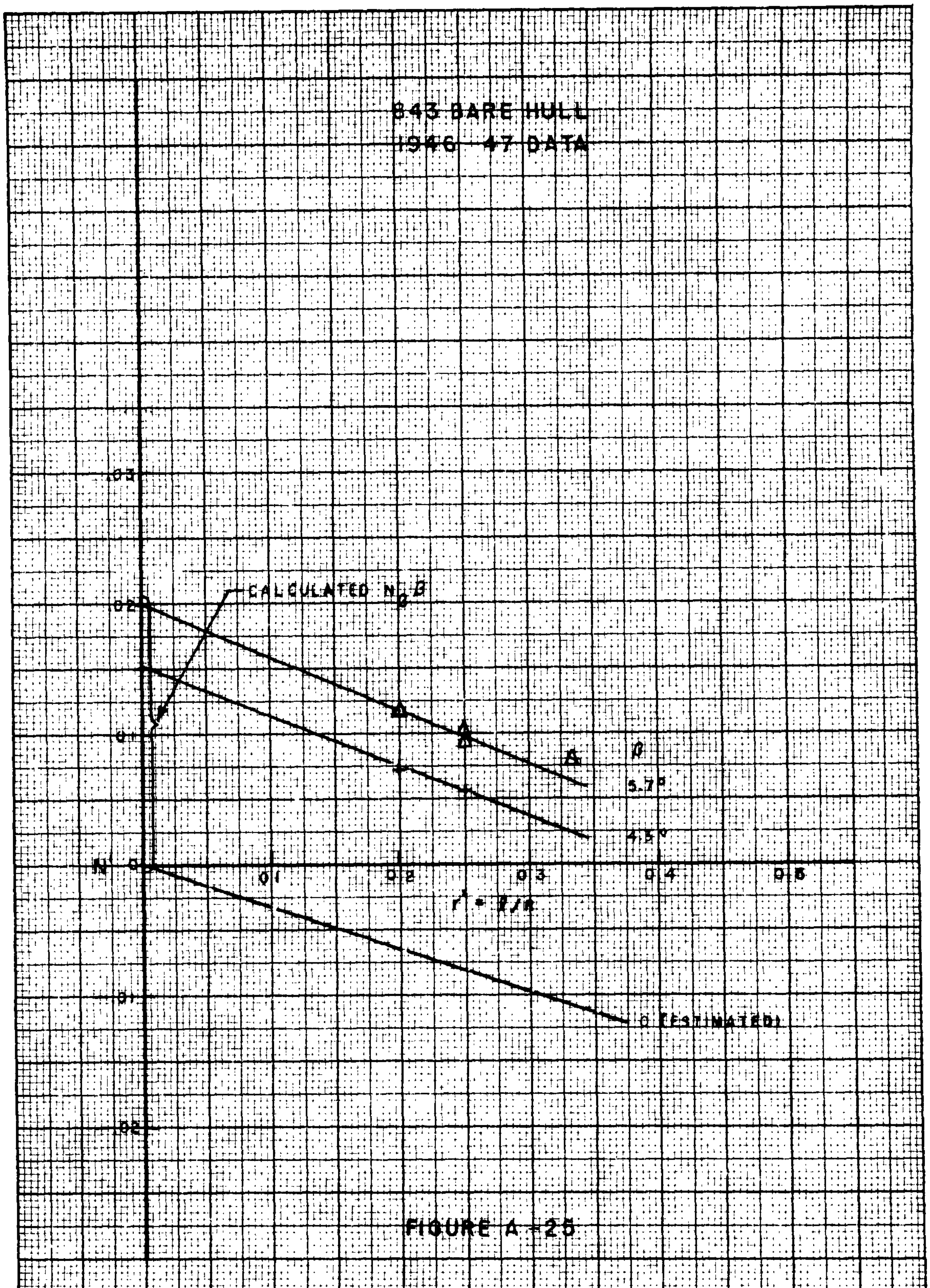

843 BARE HULL
1946 47 DATA
CALCULATED $N_{\beta}\beta$
.03
.02
.01
N' 0
.01
.02
.1
.2
.3
.4
.5
$r' = \dot{\psi}L/U$
β
5.7°
4.5°
0 (ESTIMATED)

FIGURE A-25

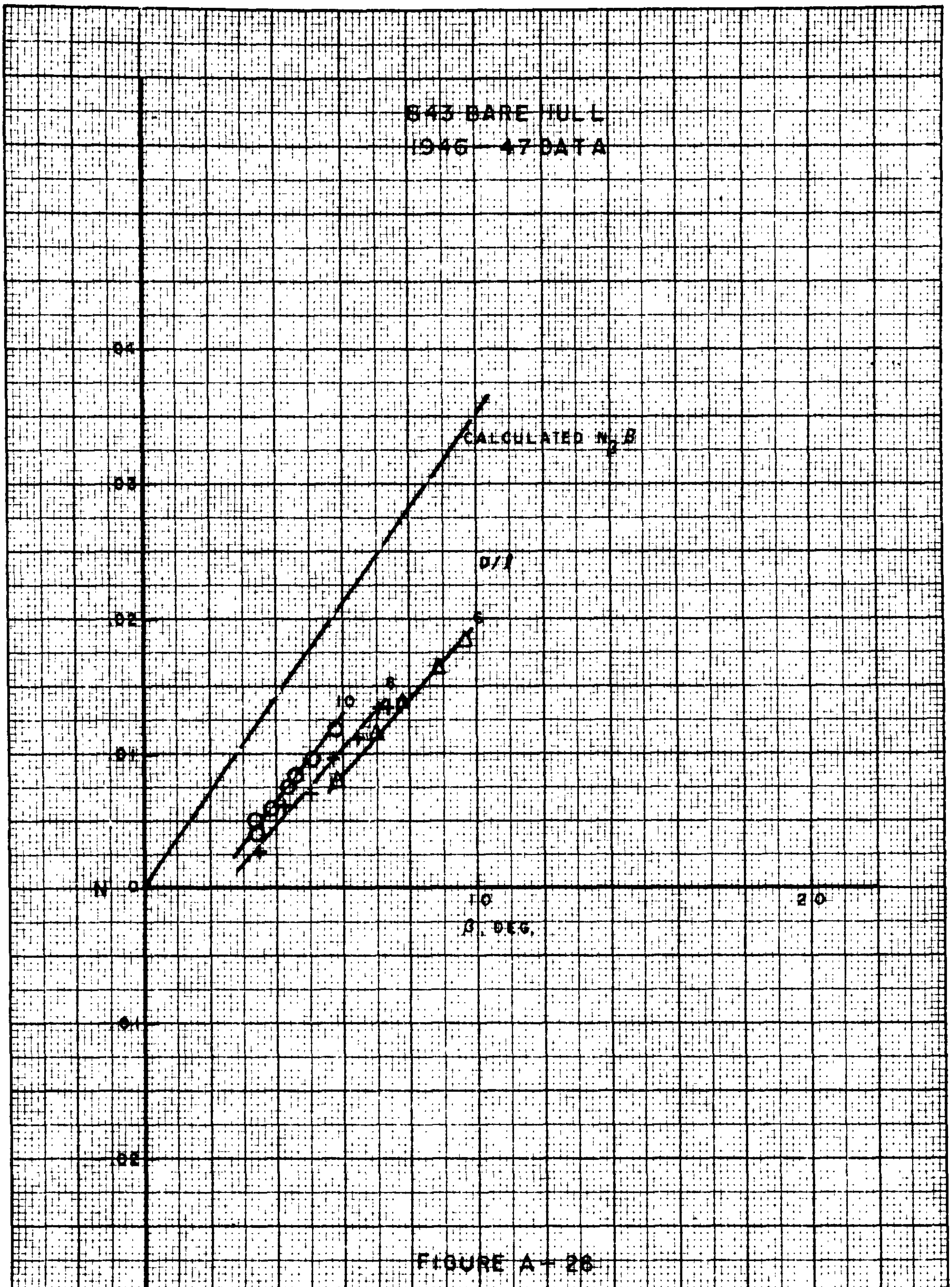
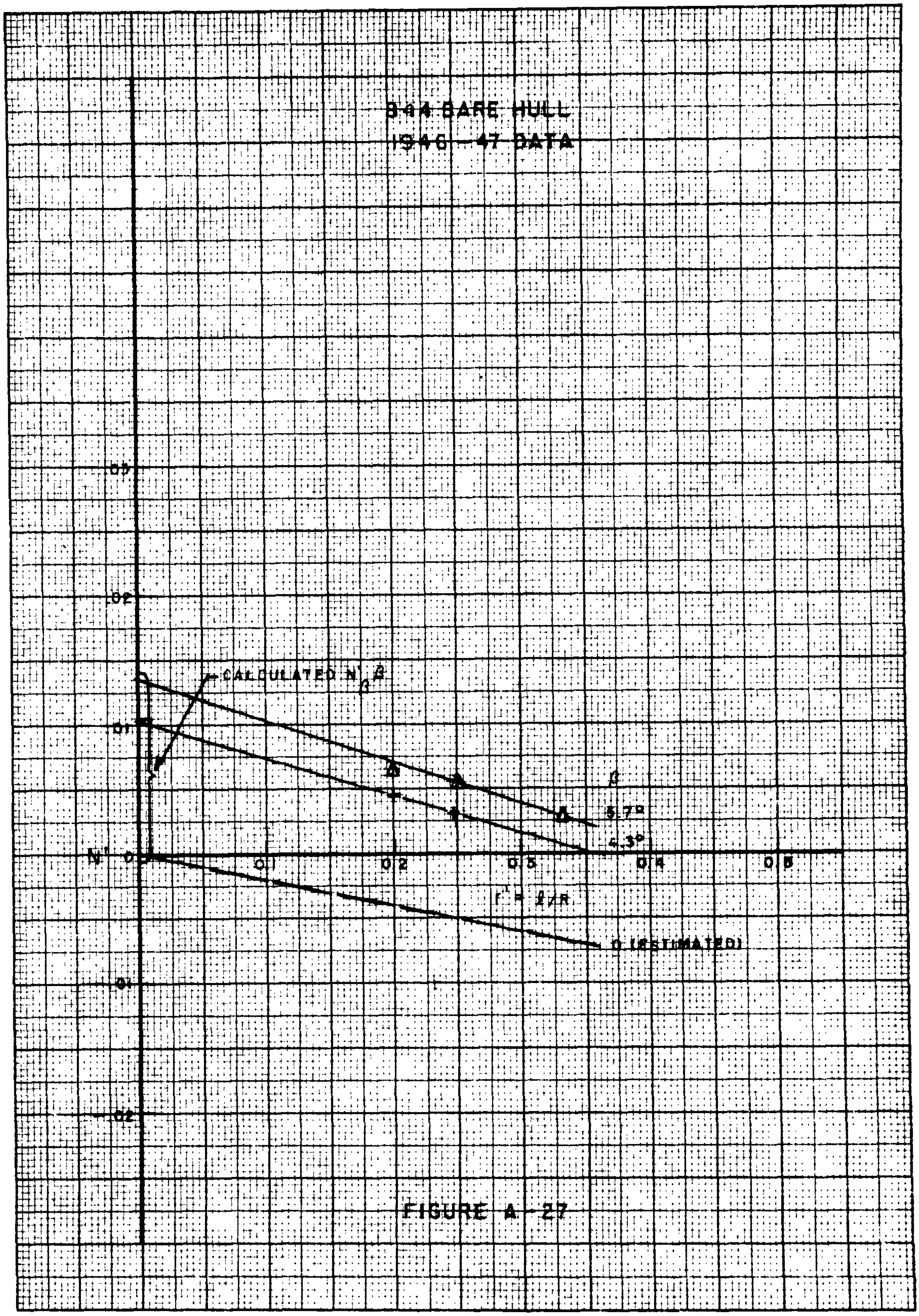
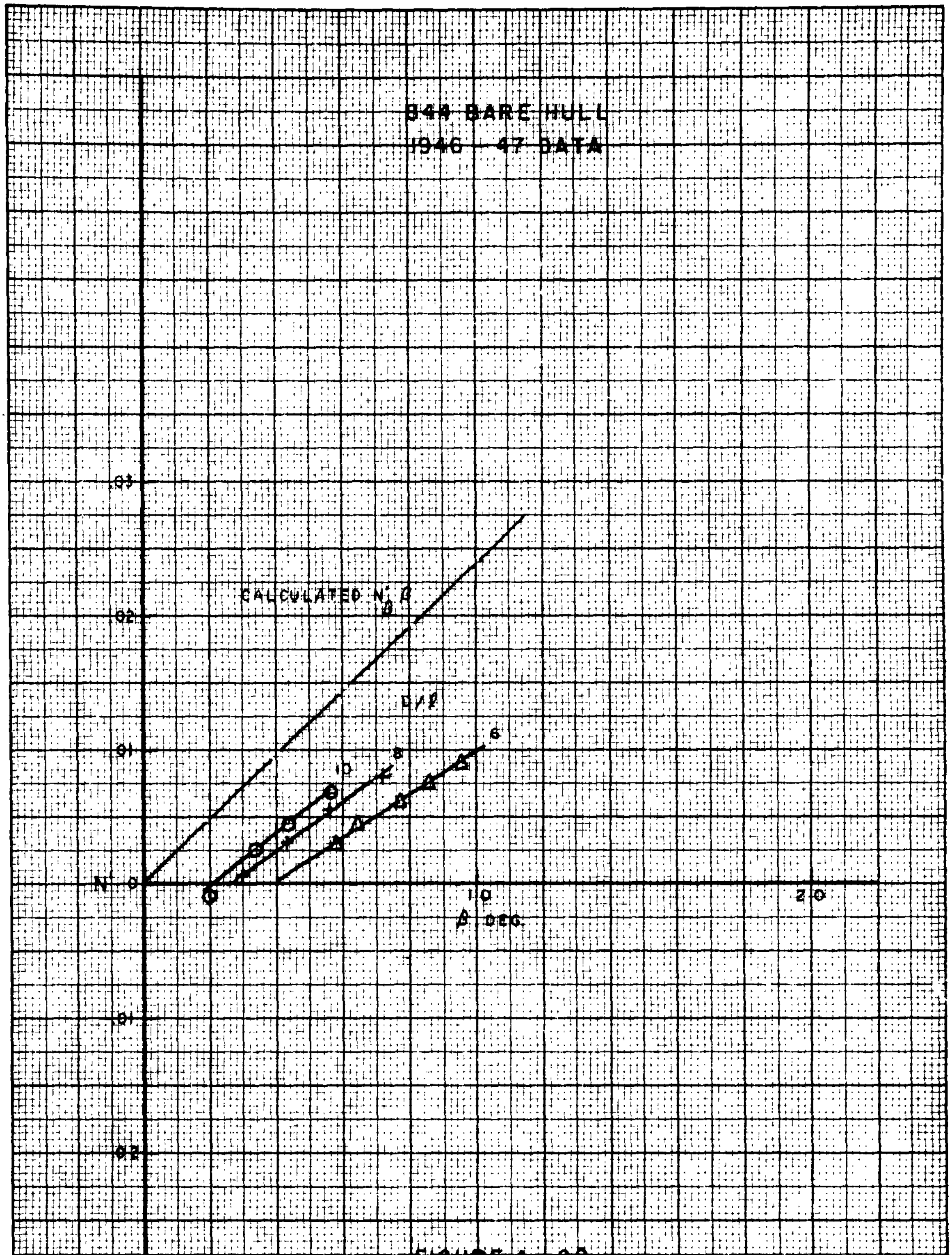

B43 BARE HULL
1946 — 47 DATA
.04
.03
.02
.01
0
N
-.01
-.02
CALCULATED $N_\beta\beta$
10
5
1.0
2.0
β, DEG.

FIGURE A — 26



344 BARE HULL
1946 - 47 DATA
CALCULATED $N'_\beta \beta$
β
5.7°
4.3°
0 (ESTIMATED)
N'
.03
.02
.01
0
-.01
-.02
0.1
0.2
0.3
0.4
0.5
$r' = \ell/R$

FIGURE A-27


B44 BARE HULL
1946 - 47 DATA
CALCULATED N'β
D/β
10
8
6
.03
.02
.01
N 0
-.01
-.02
1.0
2.0
β, DEG.
FIGURE A-28

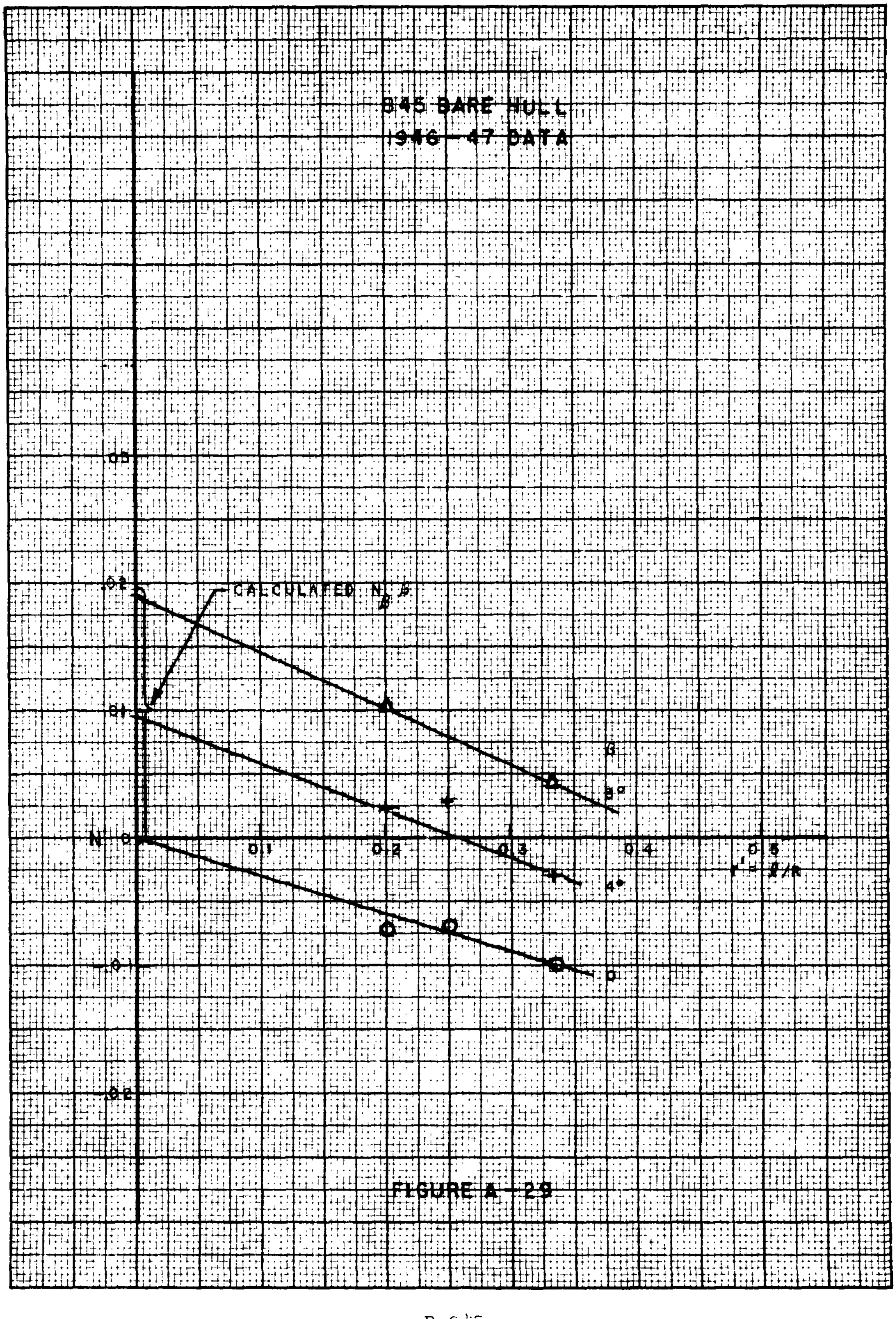

845 BARE HULL
1946—47 DATA
CALCULATED N'β
.03
.02
.01
N' 0
-.01
-.02
0.1
0.2
0.3
0.4
0.5
8°
4°
0

FIGURE A-29

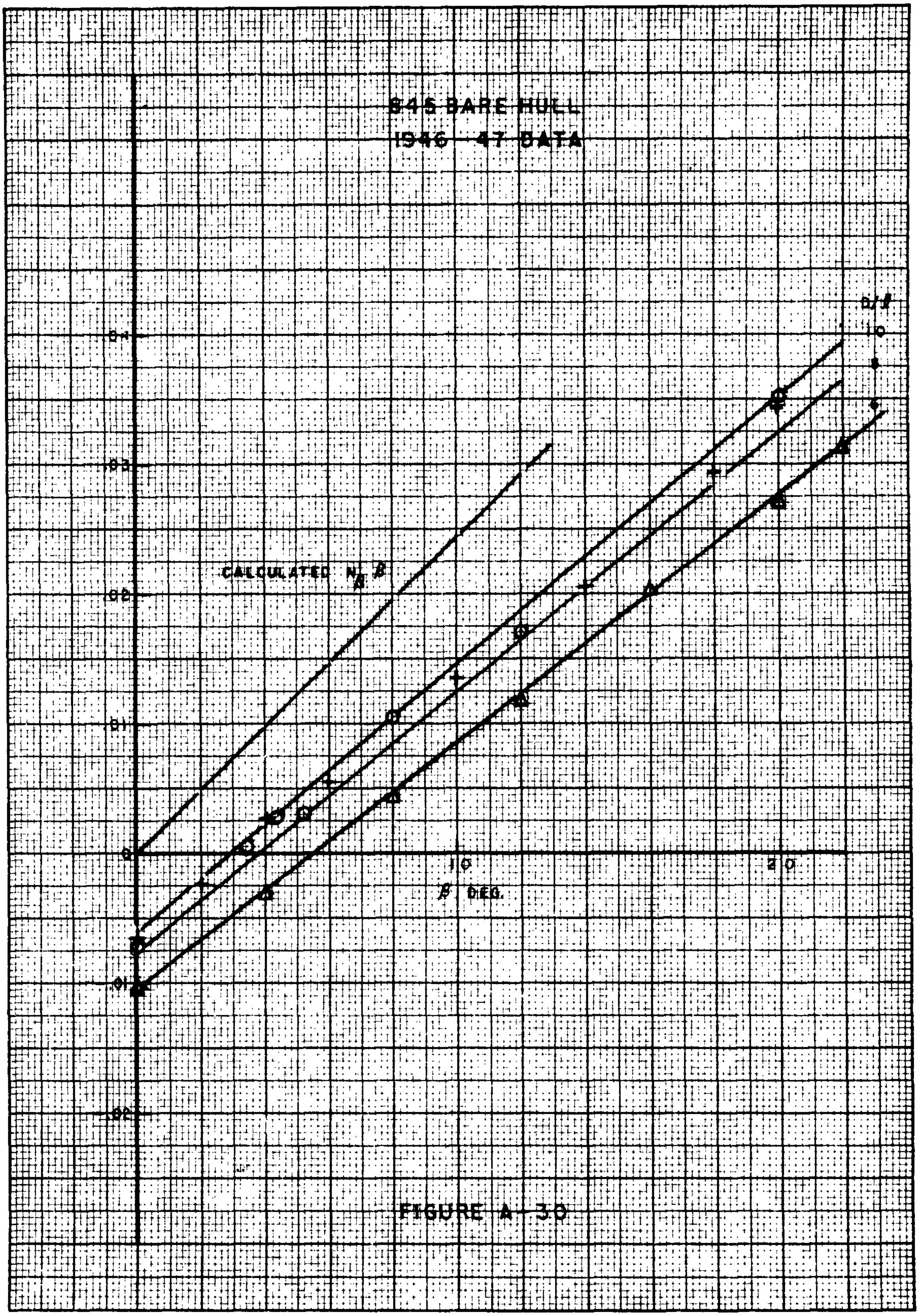
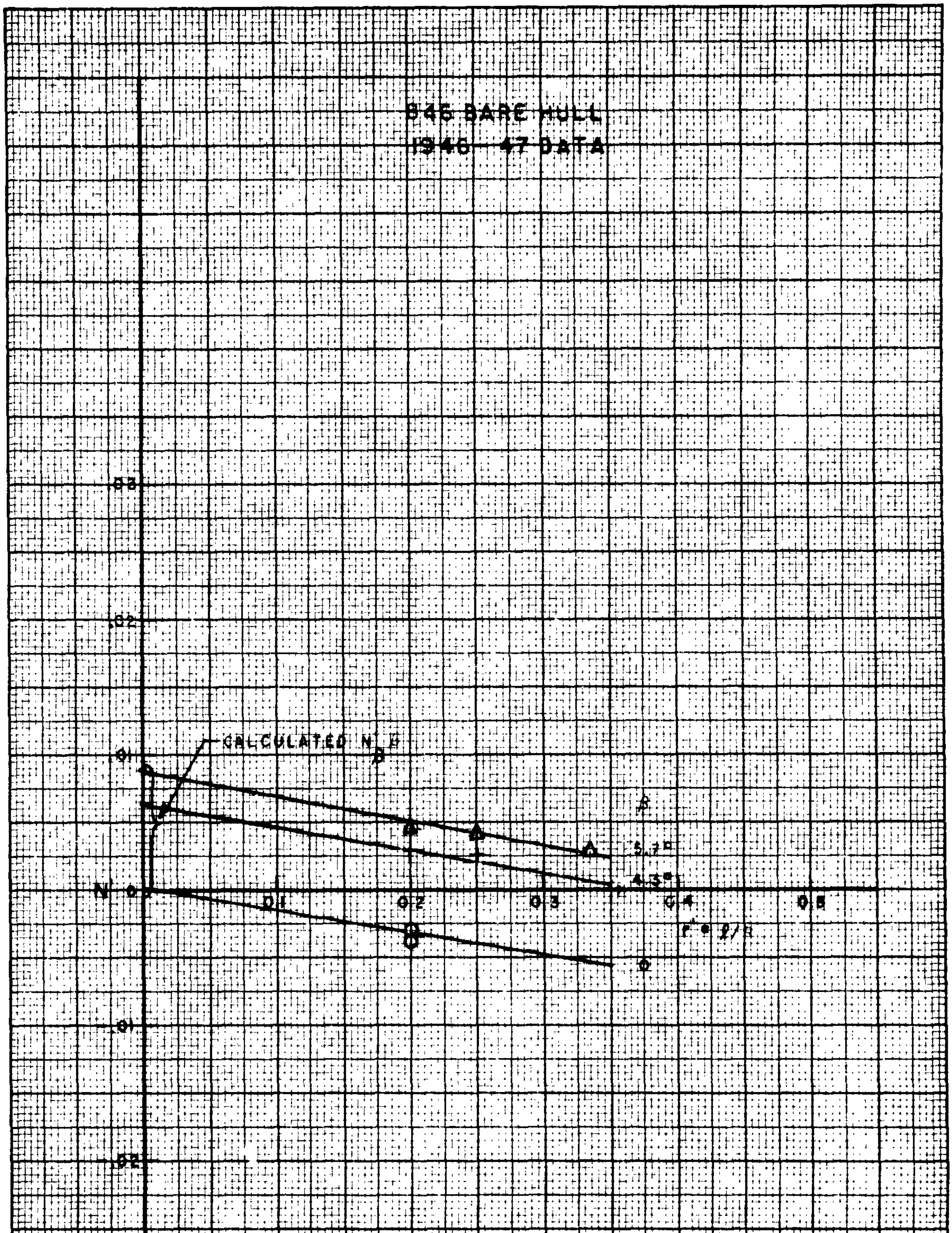
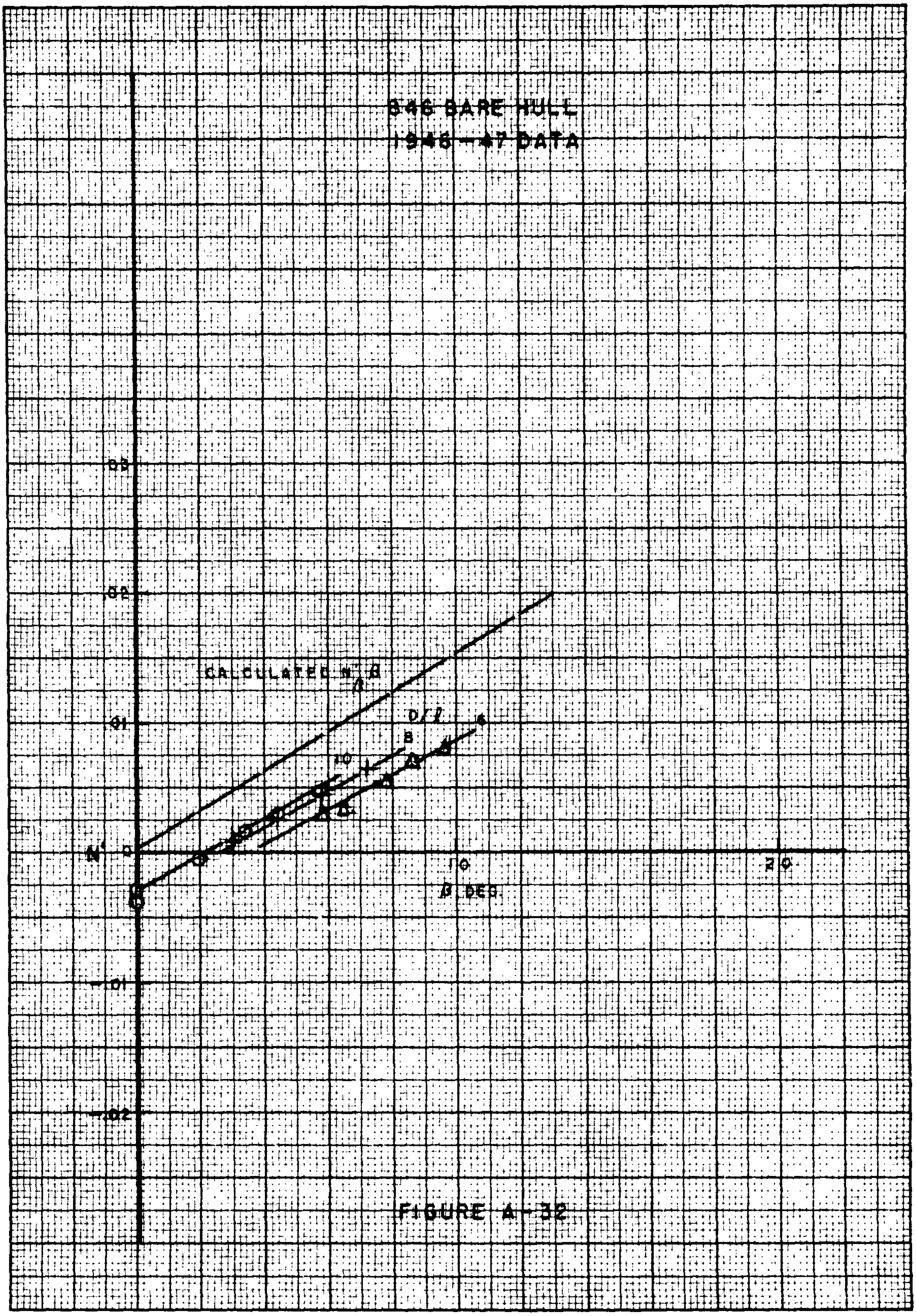

845 BARE HULL
1946 - 47 DATA
CALCULATED $N_\beta \beta$
.04
.03
.02
.01
0
.01
.02
10
20
β DEG.
10
8
6

FIGURE A-30



845 BARE HULL
1946—47 DATA
CALCULATED N_{β}
β
5.7°
4.3°
N
.03
.02
.01
0
-.01
-.02
0.1
0.2
0.3
0.4
0.5

FIGURE A-31



846 BARE HULL
1946 - 47 DATA
CALCULATED N'_β
D/ℓ
6
8
10
.03
.02
.01
0
-.01
-.02
N'
10
20
β DEG

FIGURE A-32

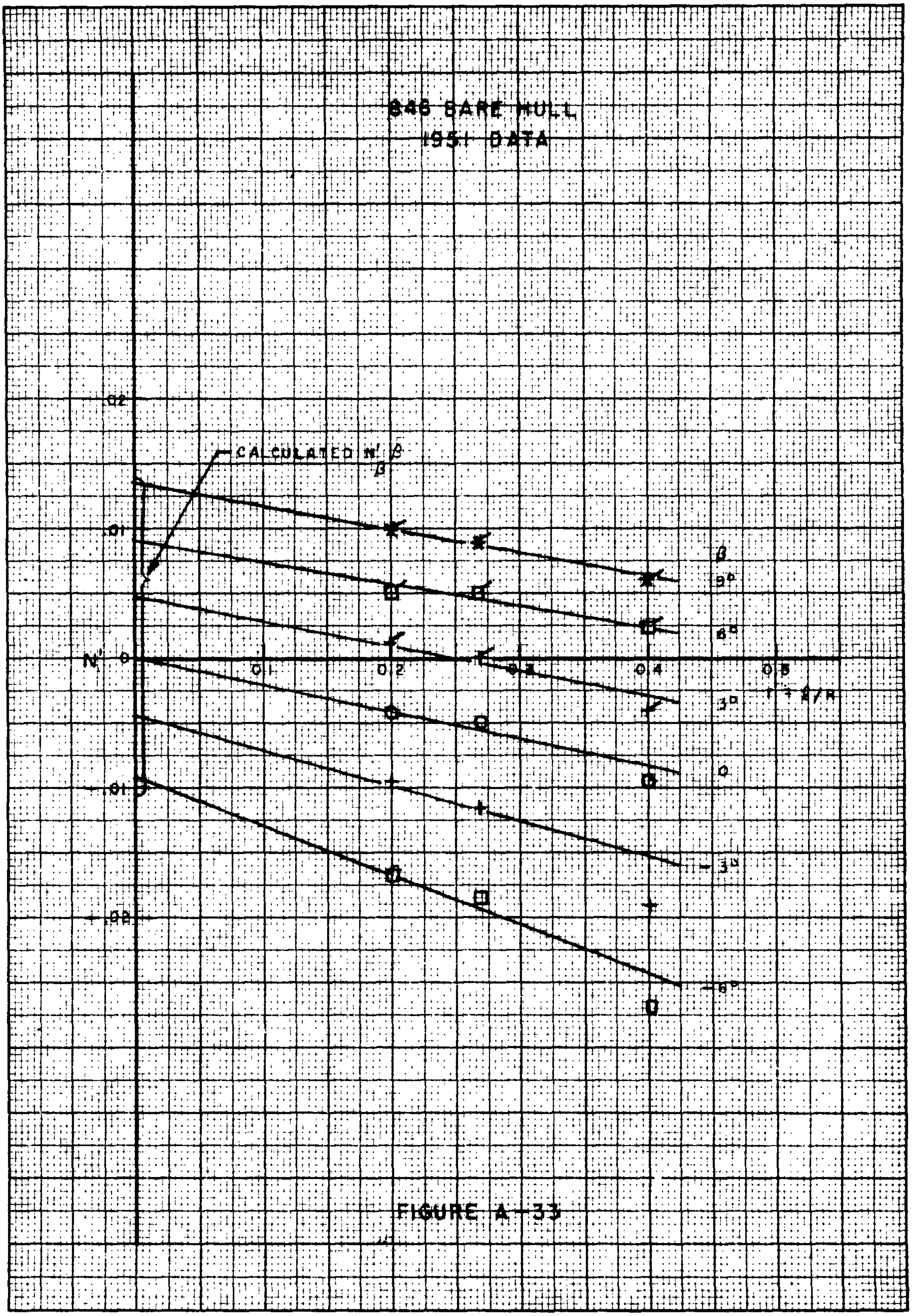

846 BARE HULL
1951 DATA
CALCULATED N'_β
N'
.02
.01
0
-.01
-.02
0.1
0.2
0.3
0.4
0.5
β
9°
6°
3°
0
-3°
-6°

FIGURE A-33

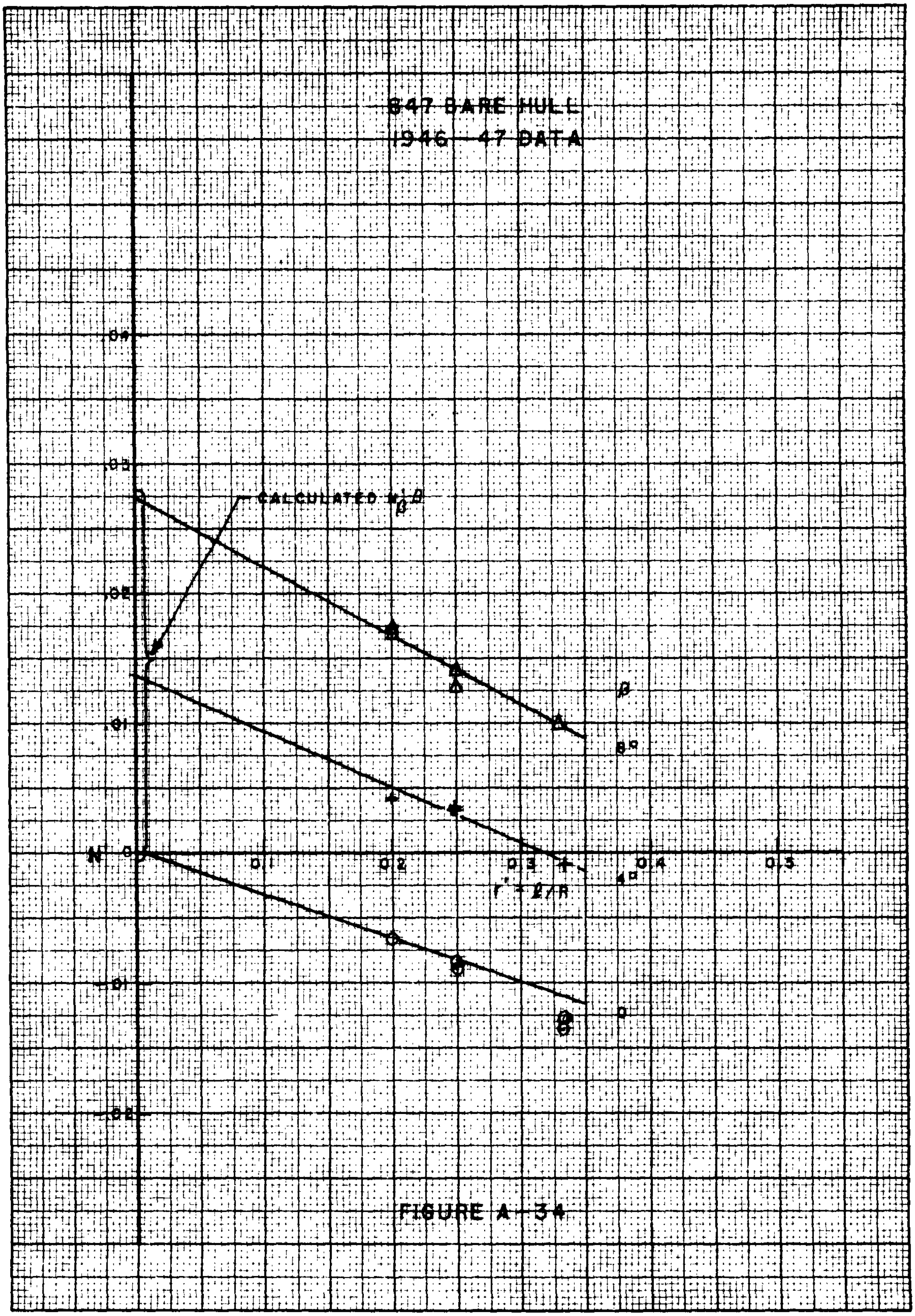

847 BARE HULL
1946 – 47 DATA
CALCULATED $N'_\beta \beta$
N'
.04
.03
.02
.01
0
-.01
-.02
0.1
0.2
0.3
0.4
0.5
$r' = \ell/R$
β
8°
4°
0

FIGURE A-34

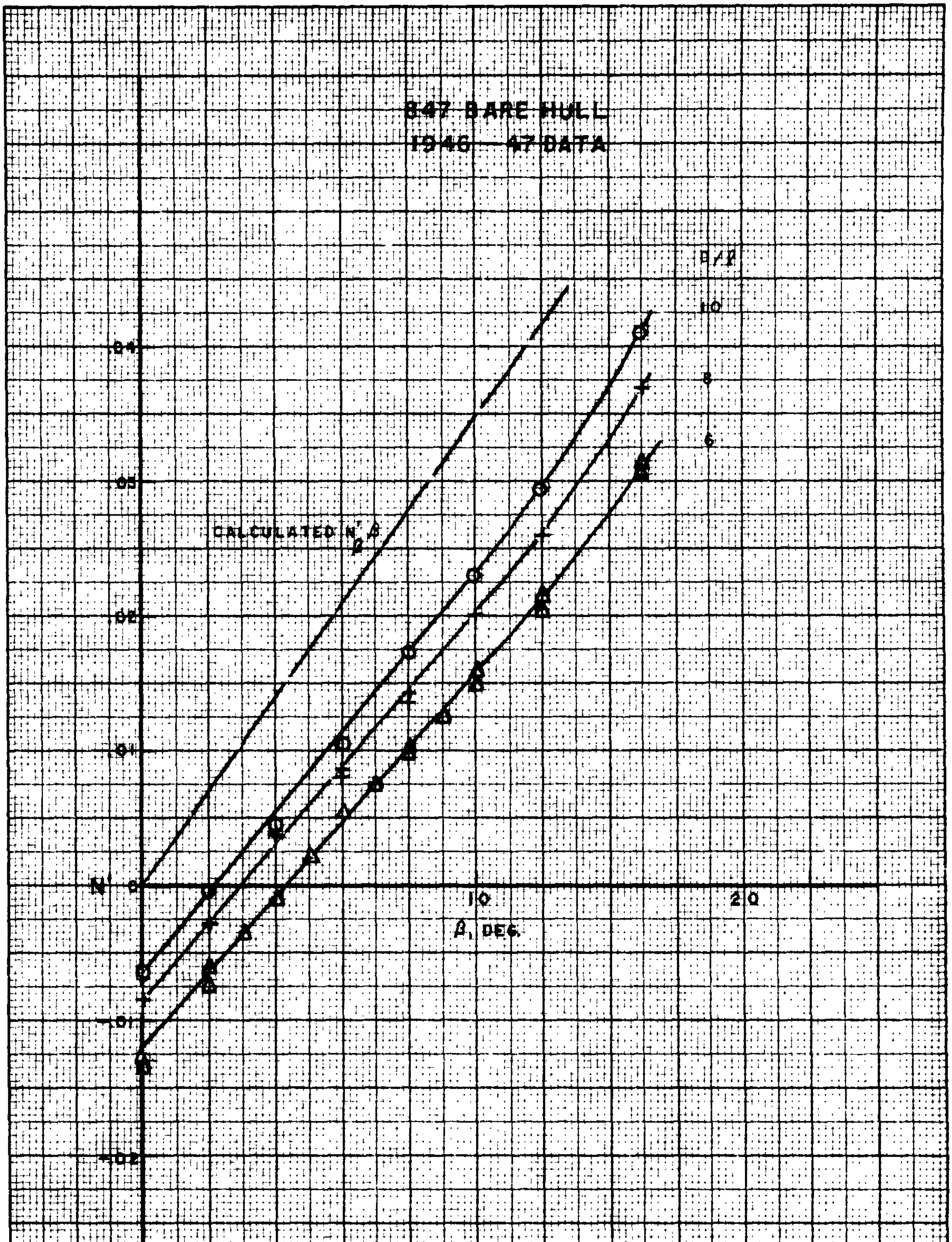
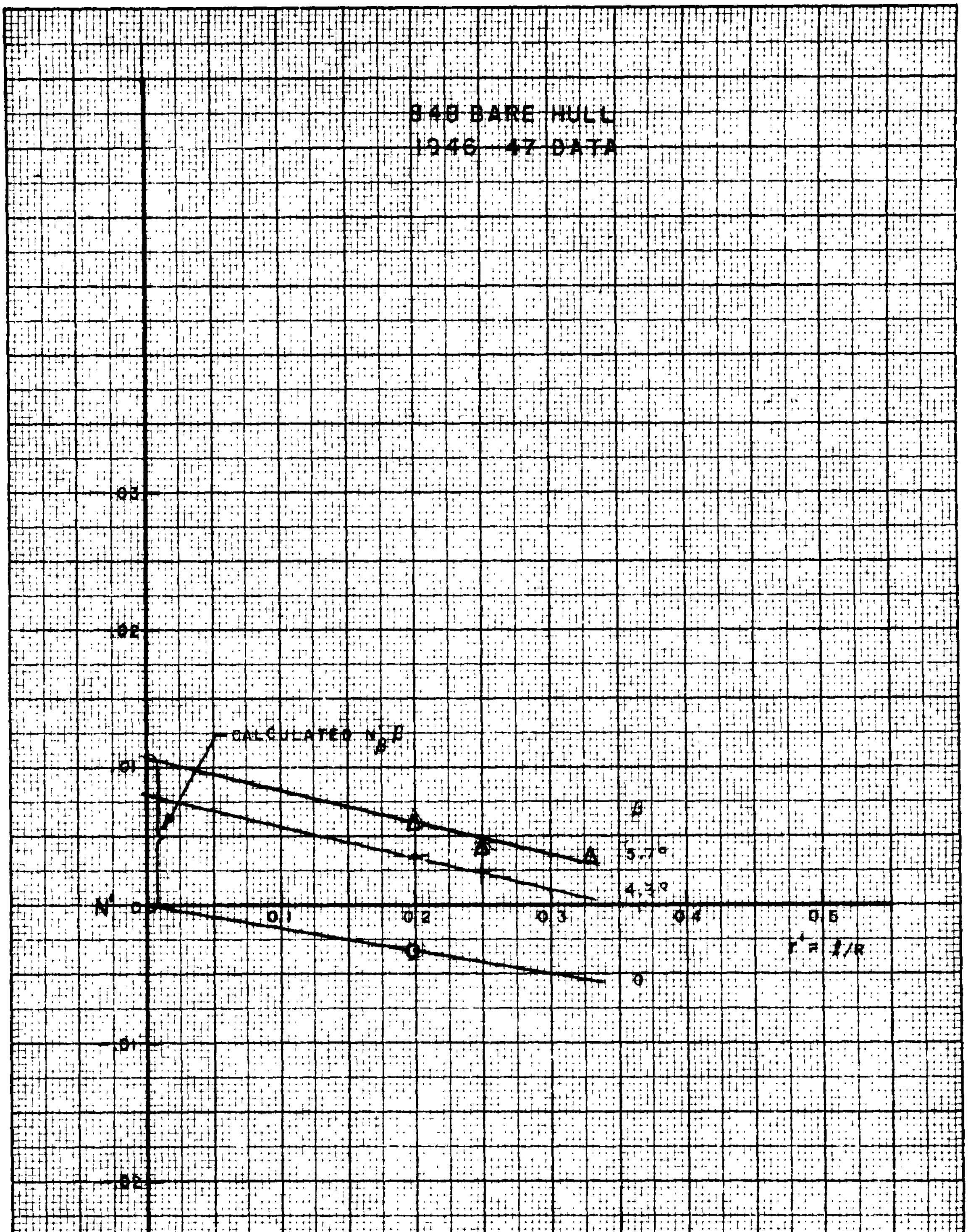
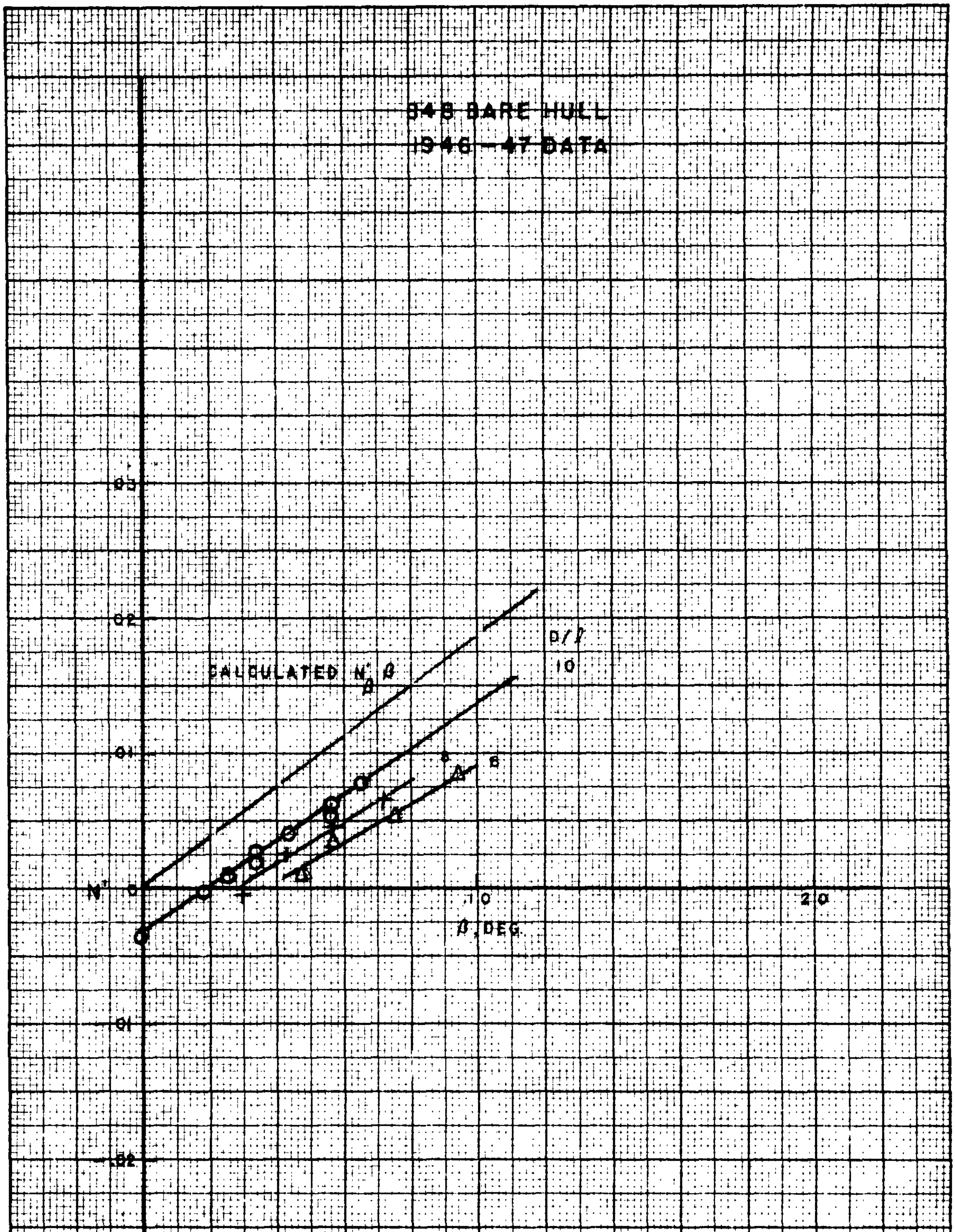

847 BARE HULL
1946 — 47 DATA
10
8
6
.04
.03
.02
.01
0
-.01
-.02
N'
10
20
β, DEG.
CALCULATED N'β β

FIGURE A-35



848 BARE HULL
1946 47 DATA
.03
.02
.01
0
-.01
-.02
N'
CALCULATED N'β β
β
5.7°
4.3°
0
.1
.2
.3
.4
.5
r' = ℓ/R

FIGURE A-36



548 BARE HULL
1946 - 47 DATA
.03
.02
.01
0
-.01
-.02
N'
CALCULATED N'β
D/l
10
8
6
10
20
β, DEG.

FIGURE A-37

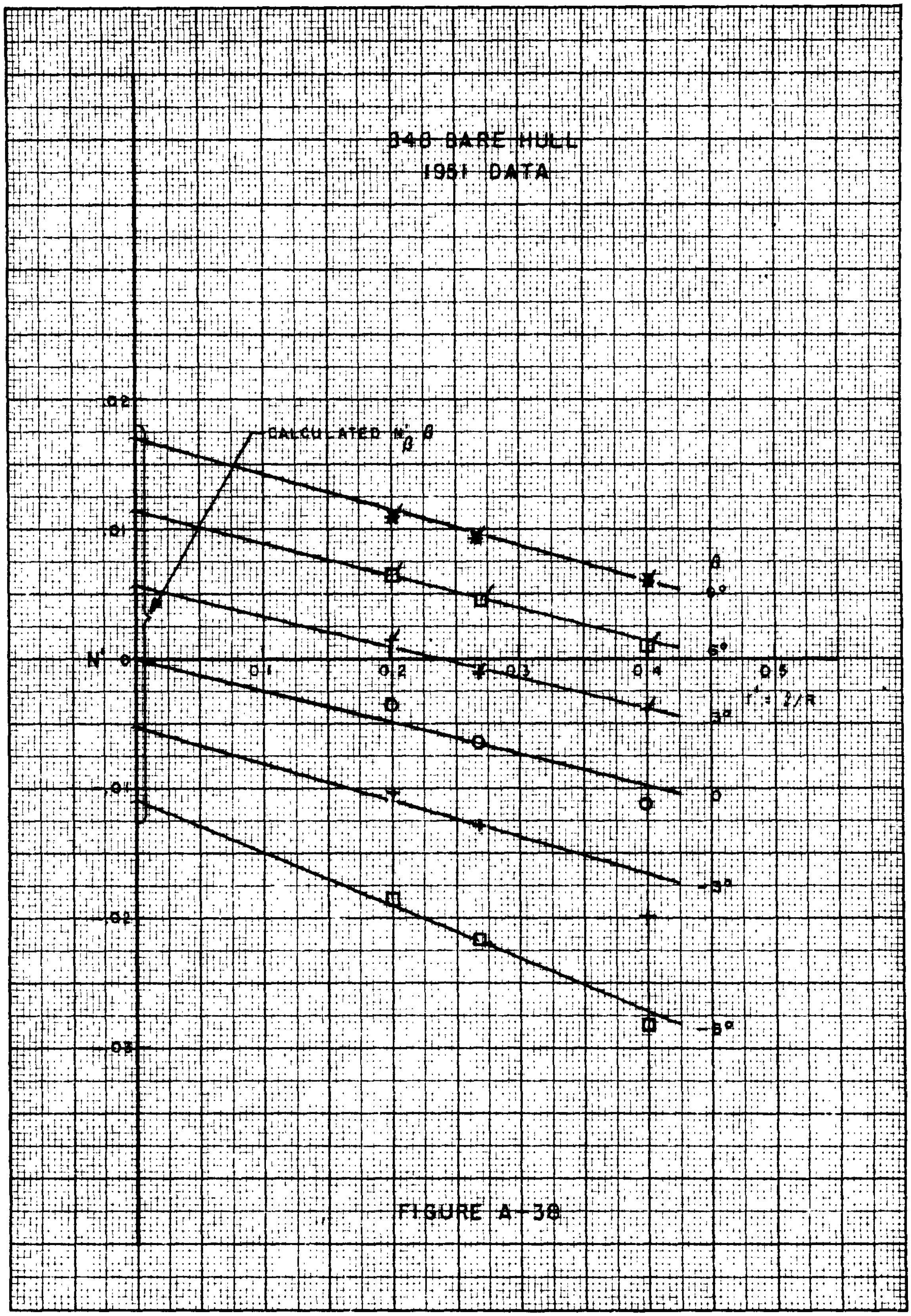

348 BARE HULL
1951 DATA
CALCULATED $N'_\beta \beta$
N'
0.2
0.1
0
-0.1
-0.2
-0.3
0.1
0.2
0.3
0.4
0.5
$r' = \ell/R$
β
6°
3°
0
-3°
-6°

FIGURE A-38

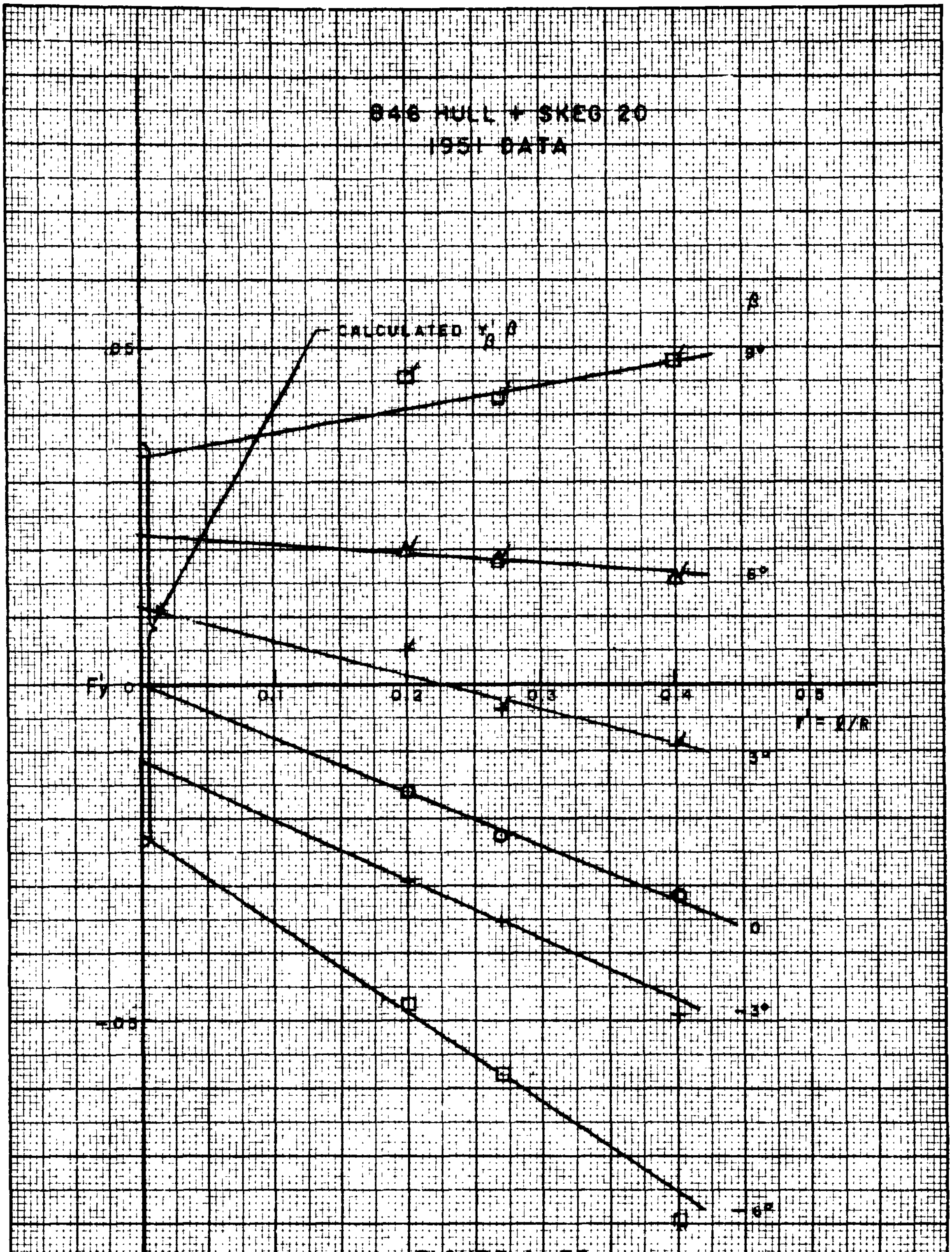

846 HULL + SKEG 20
1951 DATA
CALCULATED Y'_β β
β
9°
6°
3°
0
-3°
-6°
.05
-.05
F'_y
0
0.1
0.2
0.3
0.4
0.5
$r' = \ell/R$

FIGURE A-39

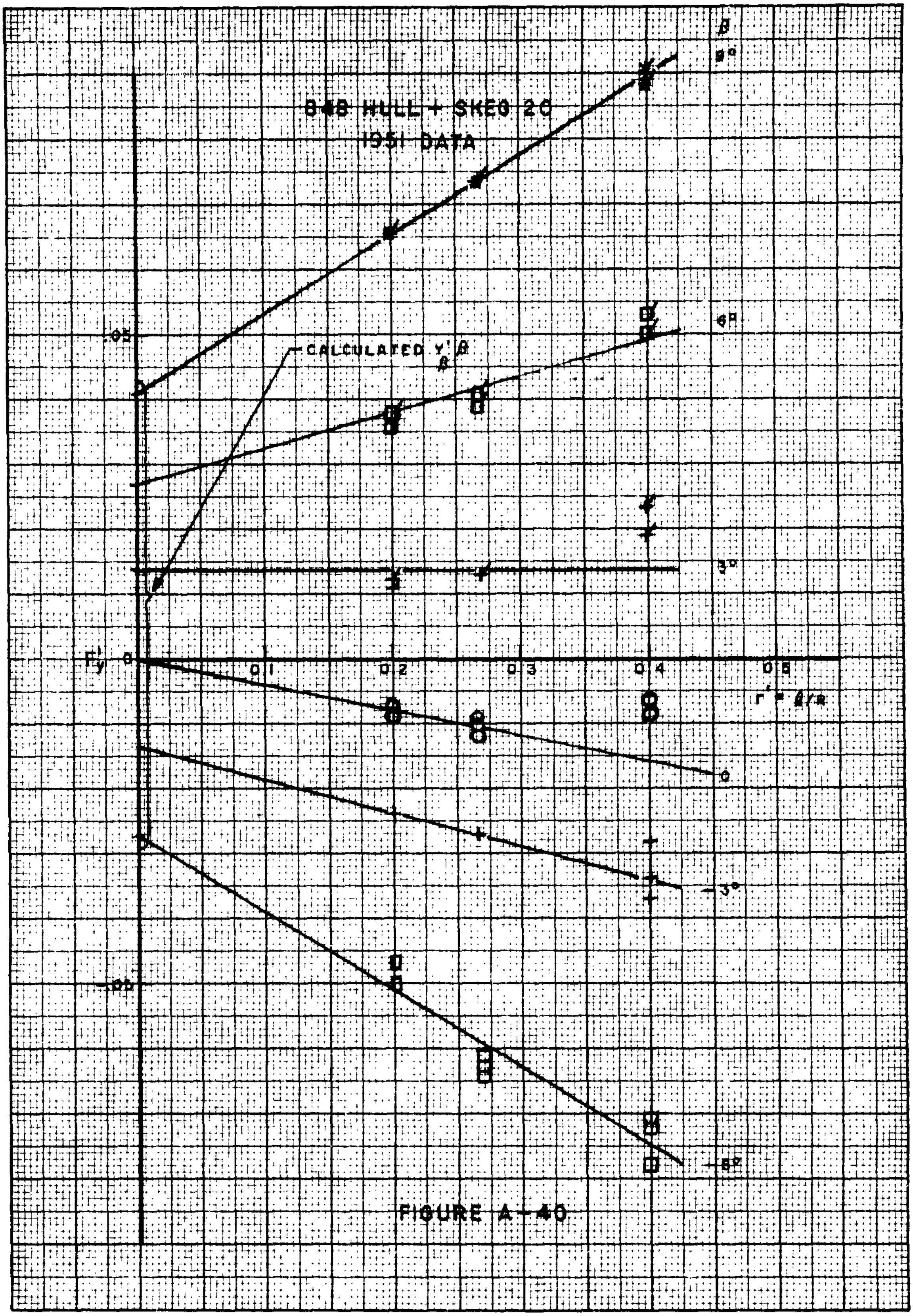

B4B HULL + SKEG 2C
1951 DATA
CALCULATED Y'β
β
9°
6°
3°
0
-3°
-6°
.05
-.05
0
.1
.2
.3
.4
.5
r' = ℓ/R

FIGURE A-40

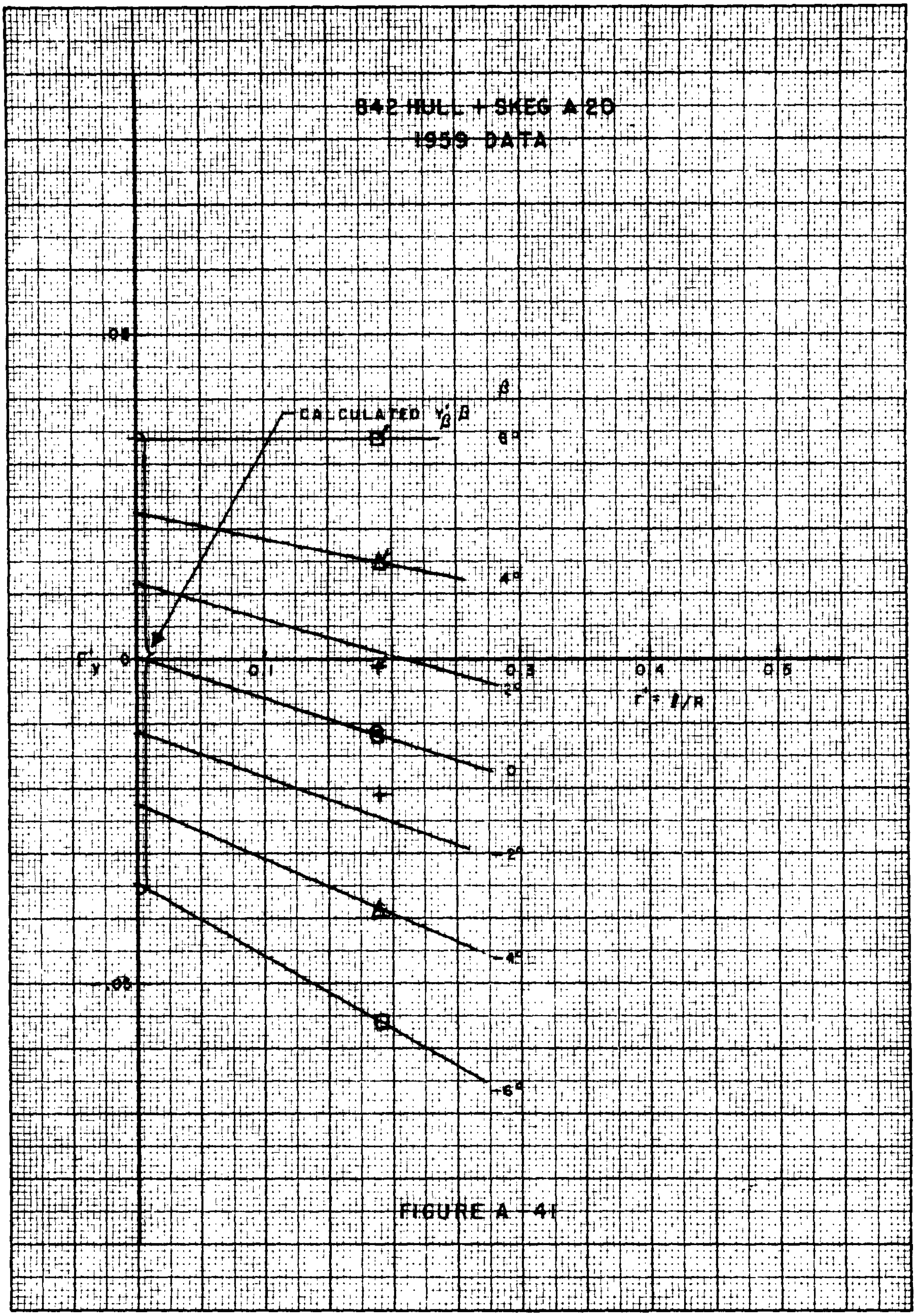
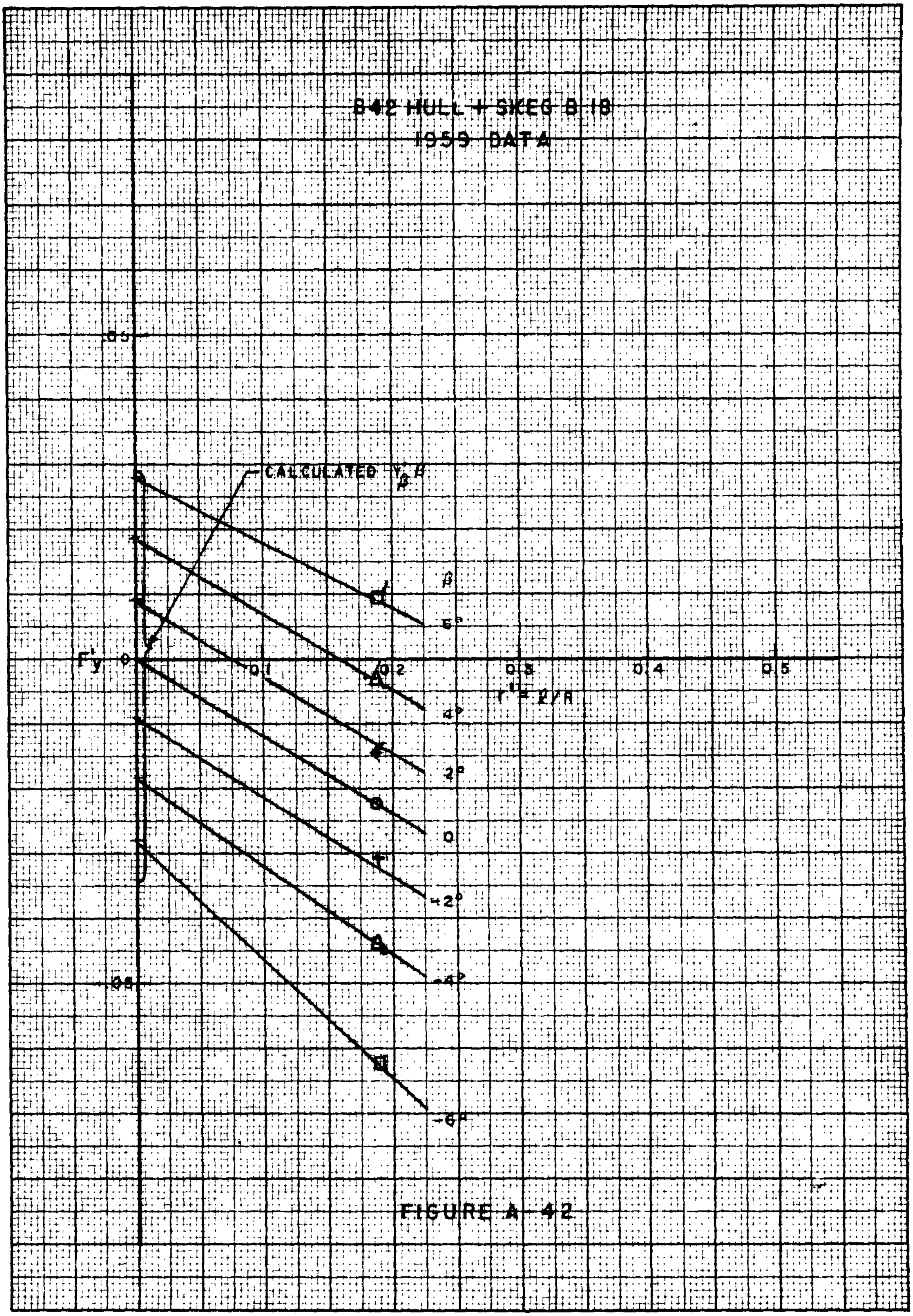

842 HULL + SKEG A 20
1959 DATA
CALCULATED $Y'_\beta \beta$
β
6°
4°
2°
0
-2°
-4°
-6°
.05
-.05
F'_y
0
0.1
0.3
0.4
0.5
$r' = \ell/R$

FIGURE A - 41



842 HULL + SKEG B 18
1959 DATA
CALCULATED $Y'_\beta \beta$
β
6°
4°
2°
0
-2°
-4°
-6°
.05
-.05
F'_y 0
0.1
0.2
0.3
0.4
0.5
$r' = \ell/R$

FIGURE A-42

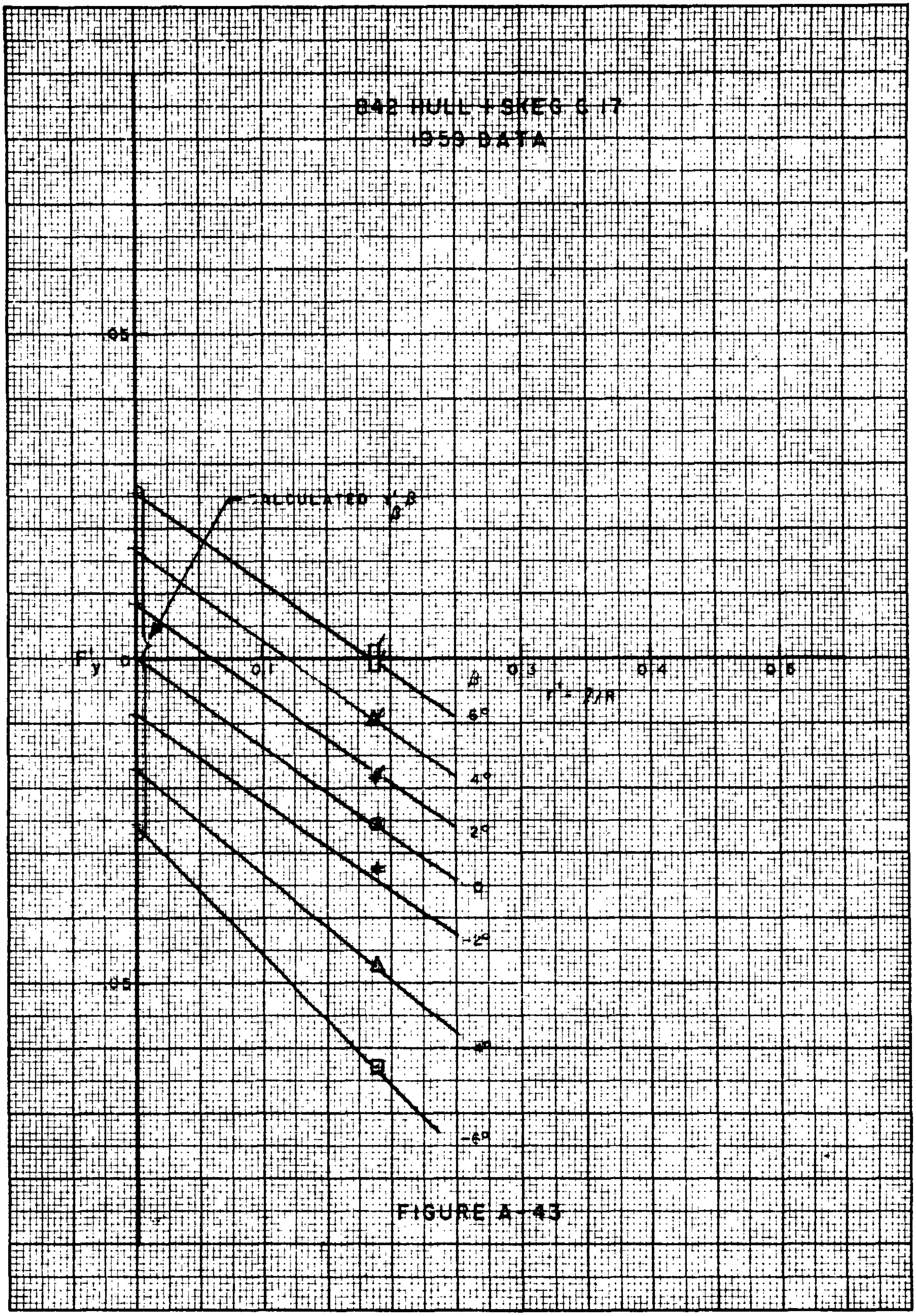

842 HULL + SKEG C 17
1959 DATA
CALCULATED $Y_\beta \beta$
F'_y
β
$r' = L/R$
6°
4°
2°
0
-2°
-4°
-6°

FIGURE A-43

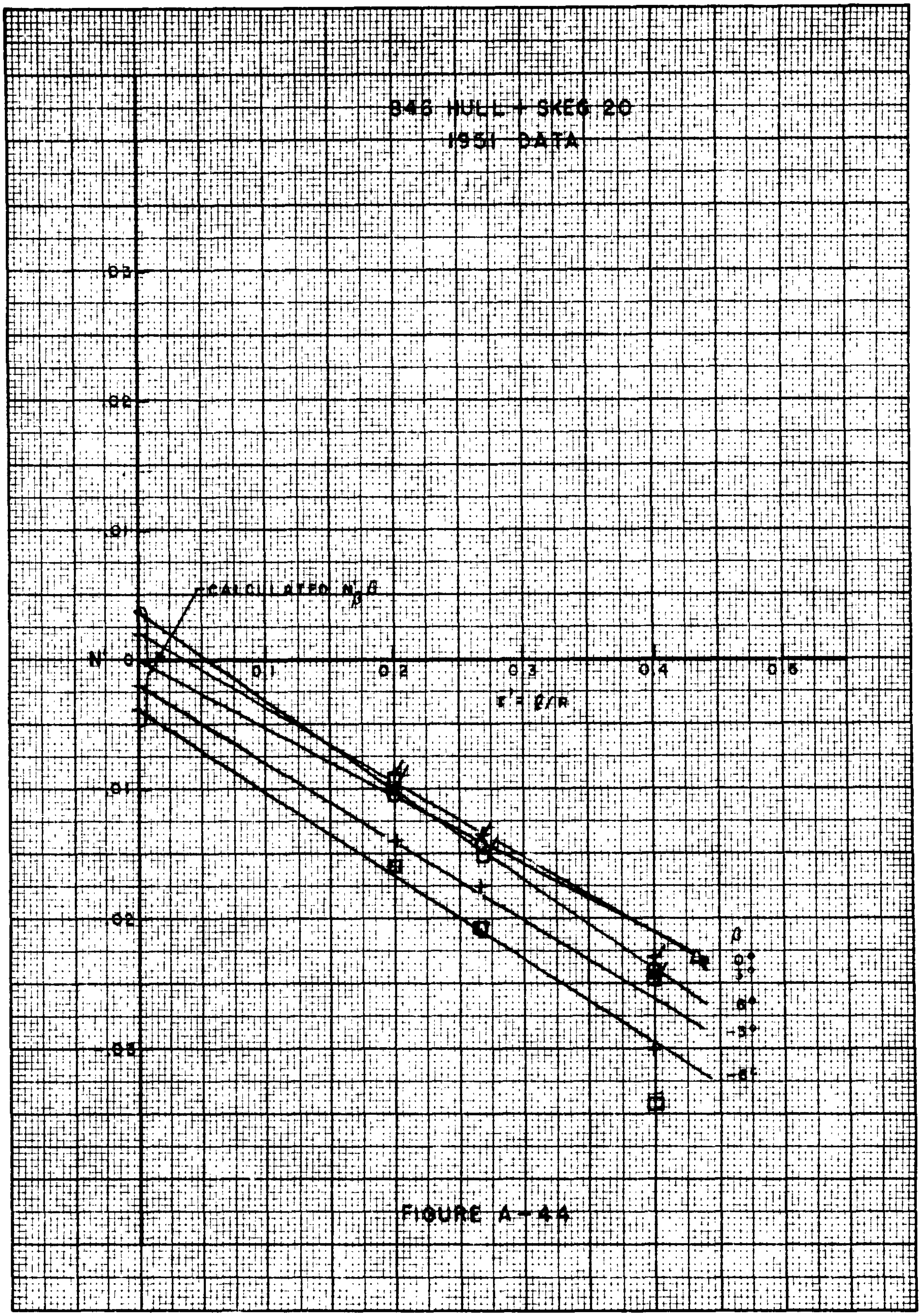


FIGURE A-44

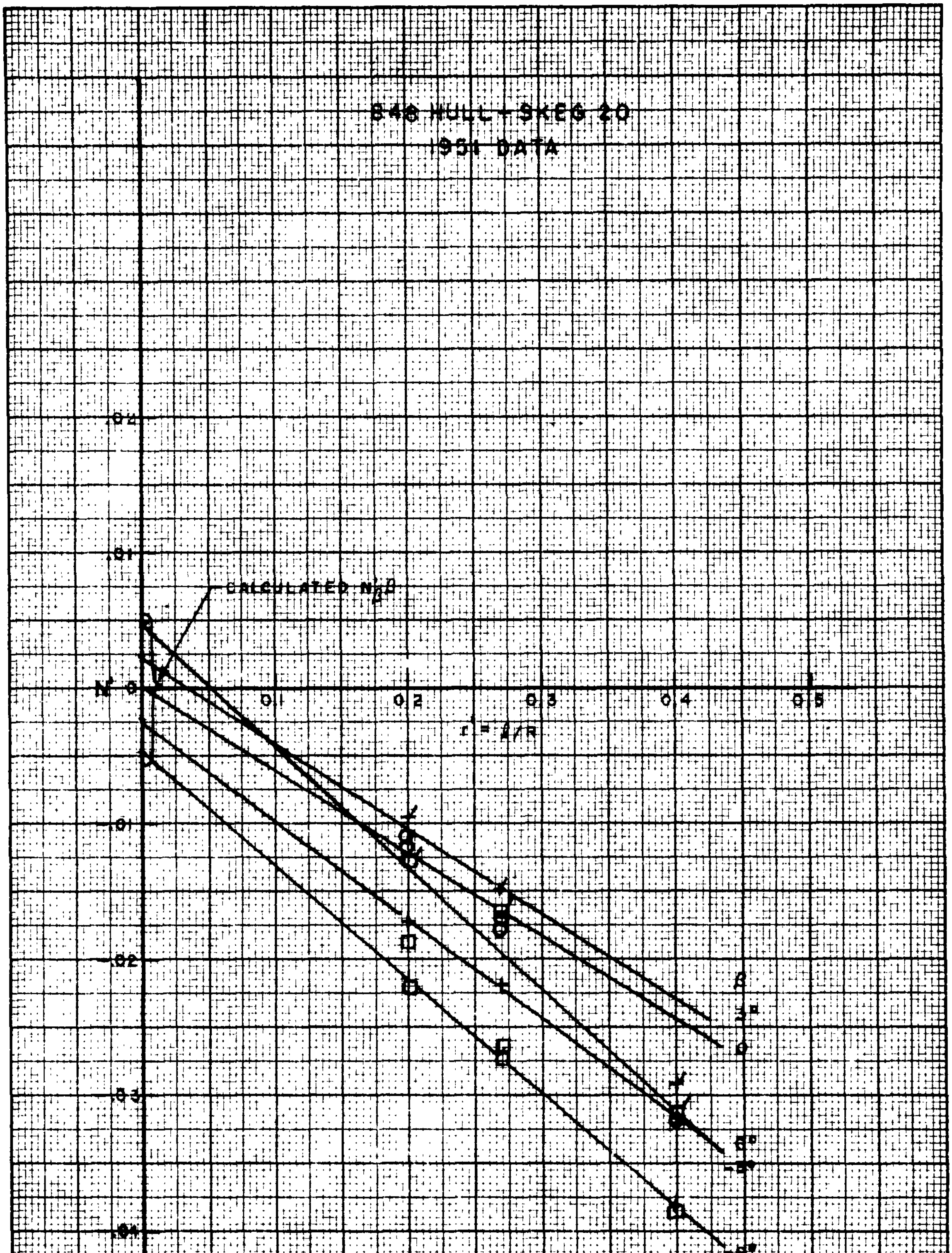

848 HULL + SKEG 20
1951 DATA
CALCULATED N'β
N'
.02
.01
0
-.01
-.02
-.03
-.04
0.1
0.2
0.3
0.4
0.5
r' = ℓ/R

FIGURE A-45

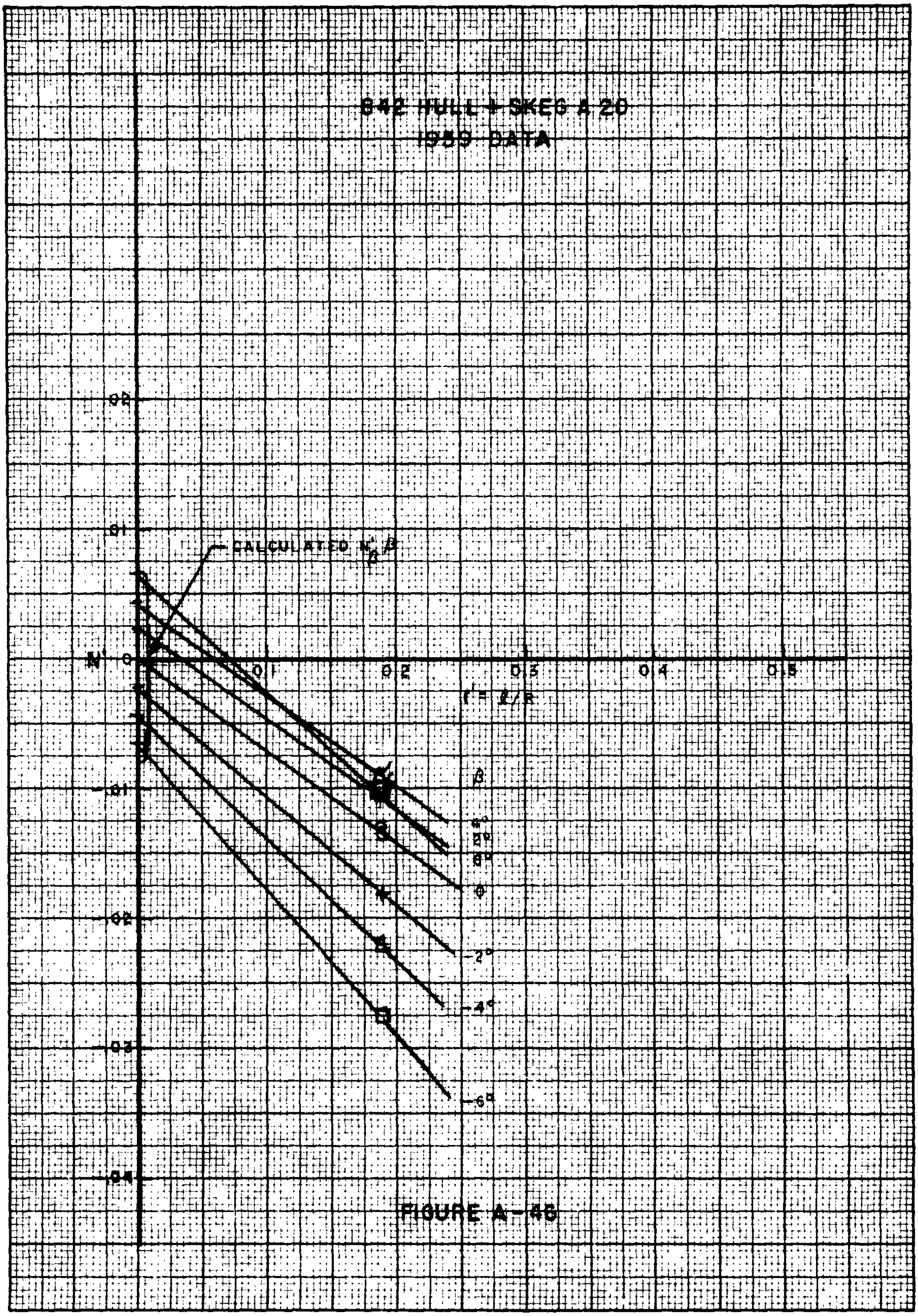

842 HULL + SKEG A 20
1959 DATA
CALCULATED $N'_\beta\beta$
N'
.02
.01
0
-.01
-.02
-.03
-.04
0.1
0.2
0.3
0.4
0.5
β
0
-2°
-4°
-6°

FIGURE A-46

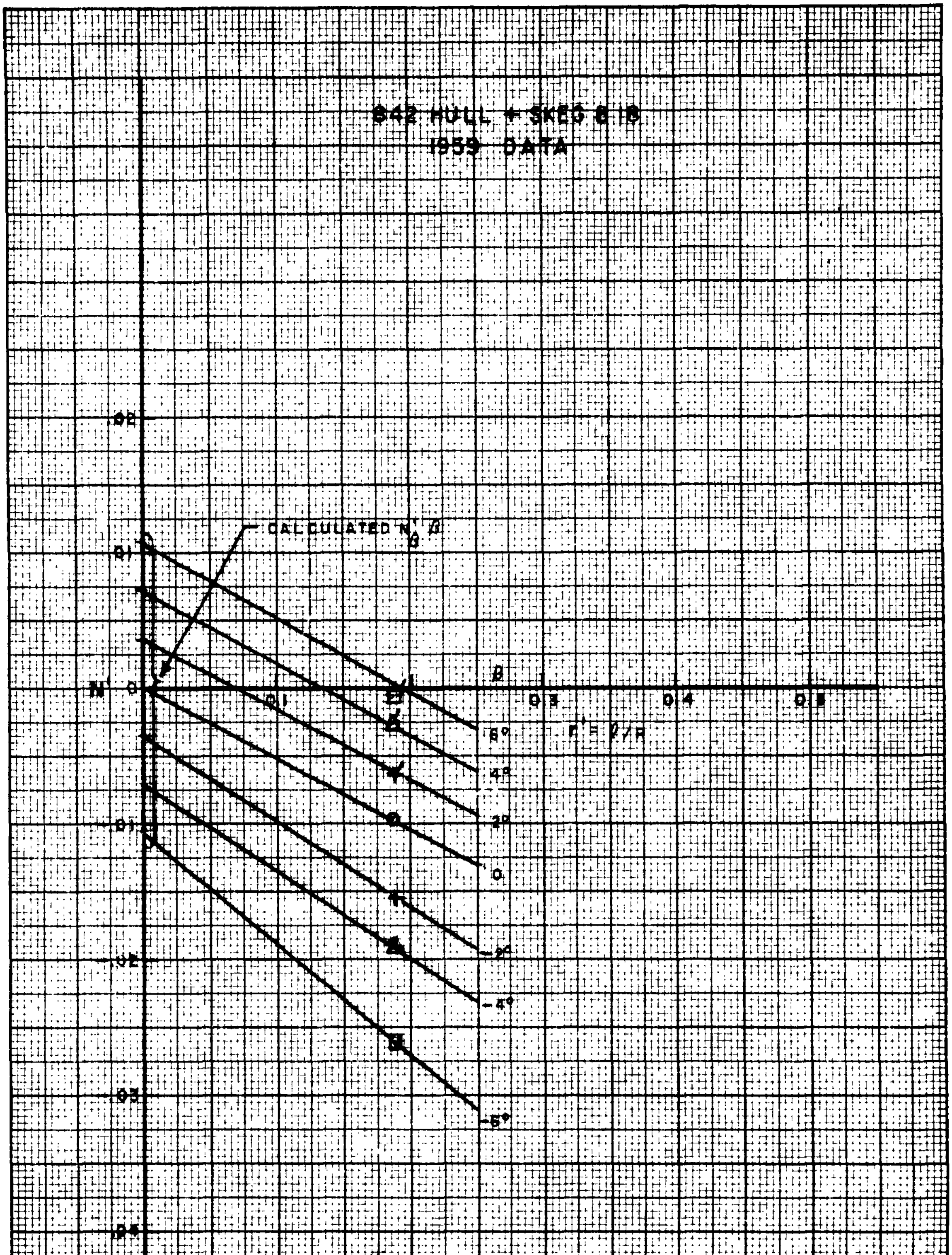

842 HULL + SKEG 818
1959 DATA
CALCULATED N'_β β
.02
.01
N' 0
-.01
-.02
-.03
-.04
0.1
0.3
0.4
0.5
β
8°
4°
2°
0
-2°
-4°
-8°
$r' = \ell/R$

FIGURE A-47

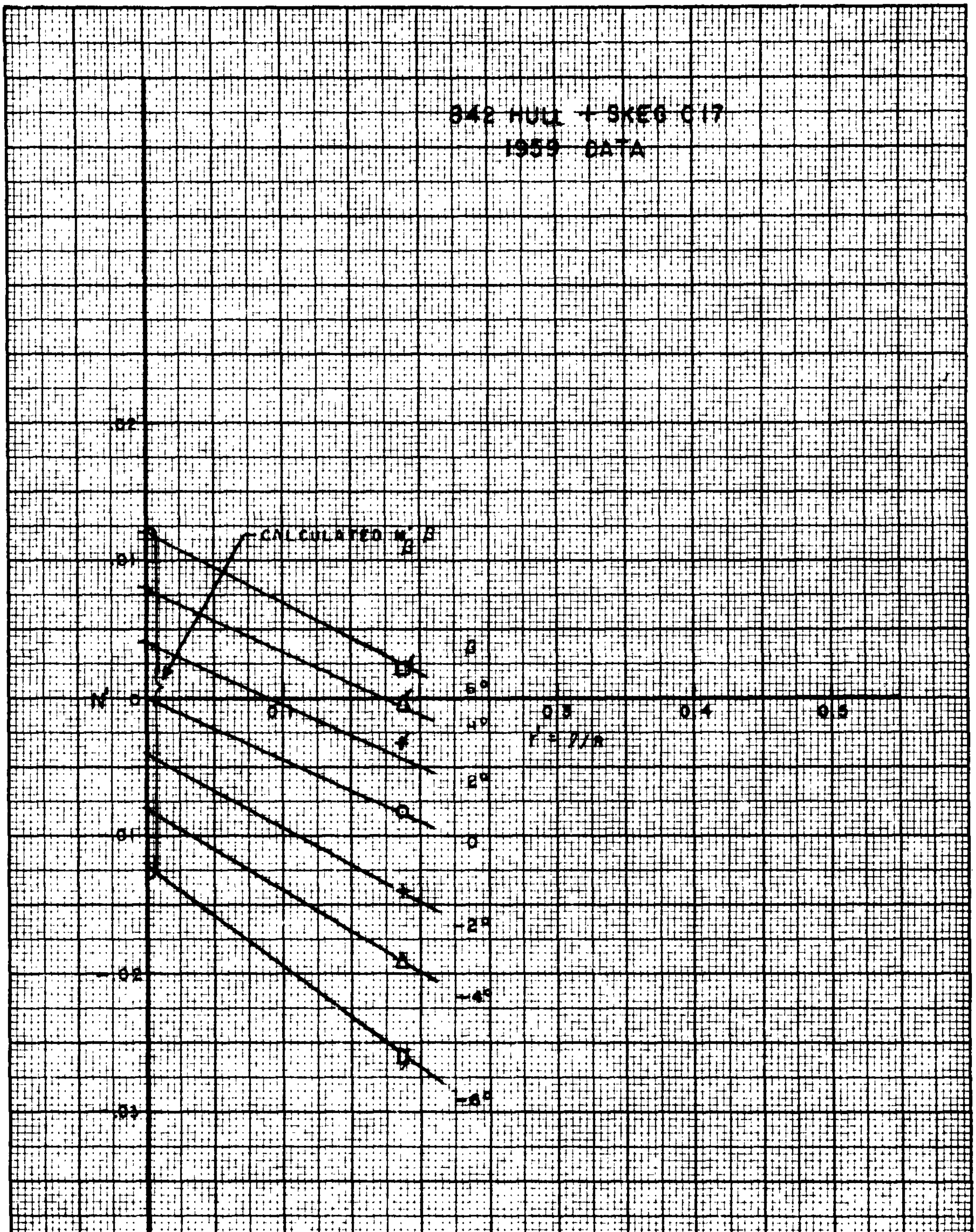

842 HULL + SKEG C17
1959 DATA
CALCULATED N'_{β}
β
6°
4°
2°
0
-2°
-4°
-6°
N'
$r' = rL/V$
.02
.01
0
-.01
-.02
-.03
-.04
0.1
0.3
0.4
0.5

FIGURE A-48

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by Winnifred R. Jacobs

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An analytical method combining simplified potential flow theory and low aspect-ratio wing theory with empirical modifications for a real viscous fluid is used to predict the stability derivatives (first order hydrodynamic force and moment derivatives) of a family of hulls in order to estimate the dependence on geometric characteristics of course stability and turning or steering qualities. The hulls are Taylor Standard Series forms with after deadwood removed and have the same length and prismatic coefficient but varying length-draft and beam-draft ratios and skeg area. Comparison between the values calculated by this method and those obtained from experimental measurements shows good agreement. The analytical method can predict the relative effects of the geometrical characteristics. Calculated magnitudes are slightly different from the experimental but are on the conservative side. However, since the hulls tested have the same prismatic, the empirical modification for the rotary moment derivative which is a function of prismatic coefficient has not been fully tested. Necessary refinements of the method must wait on analysis of data on series of forms with different prismatic as well as length-draft and beam-draft ratios.

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